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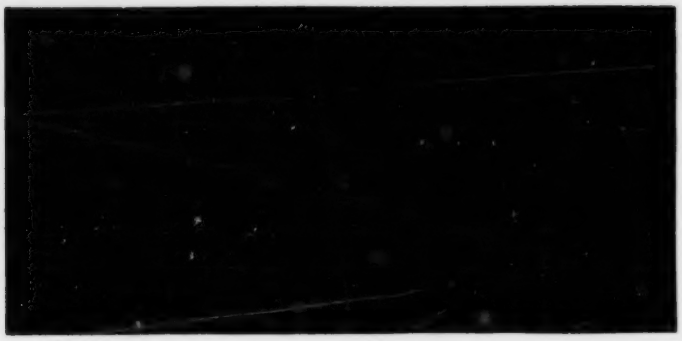
PREVENTION OF EXCESS SNOW ACCUMULATIO
DUE TO ROOF MOUNTED SOLAR COLLECTORS



PREVENTION OF EXCESS SNOW ACCUMULATION DUE TO ROOF MOUNTED SOLAR COLLECTORS

Project undertaken jointly by the Ontario Ministries of Municipal Affairs and Housing and Energy under the Housing Energy Management Program (H.E.M.P.)

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PART - I

SUMMARY

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1. TASK

This study was undertaken to review existing information and conduct model studies on the snow accumulations around various configurations of roof mounted solar collectors. The main objective was to determine which configurations would not cause accumulations in excess of those that would occur on the roof without the solar collectors.

This information would be of use in situations where the solar collectors are to be mounted on an existing roof. Under these circumstances it would be preferable not to have to strengthen the roof in order to carry an extra snow load.

2. REVIEW OF EXISTING INFORMATION

The review of existing information revealed that there is little in the published literature that gives guidance on the expected snow accumulations and only some very rough and ready rules on how to avoid excessive snow build up. However, the importance of maintaining an adequate vertical gap between the bottom of the solar collectors and the roof has been stressed by several authors and the tendency for such a gap, if it is too small, to become blocked by snow sliding off the collectors has also been noted. Solar collectors with an insufficient or blocked gap shelter the roof from the beneficial scouring action of the wind or in some circumstances act like snow fences, causing local drifts to form.

3. MODEL TESTS

The present model tests were carried out using two approaches. In the first the sand - water

analogue of snowdrifting was employed and the tests took place in a water flume using 1:200 scale models. In the second approach wind speed patterns near to the roof surface were measured on 1:50 scale models in a 1.2m x 2.4m boundary layer wind tunnel. From the sanddrift and wind speed patterns conclusions were drawn as to the propensity of particular solar collector configurations to cause snow build up. The analysis of the model results consisted principally of comparing various configurations with each other and with the bare roof case, rather than attempting the difficult task of predicting actual full scale accumulations. In this way the uncertainties in extrapolating model simulations of snowdrifting phenomena up to full scale were to a large extent avoided. The water flume and wind tunnel results were in substantial agreement with each other in comparable cases. The variables examined in the tests, some more exhaustively than others, were the position of the collector row on the roof, the gap between collector and roof, the angle of tilt, the number of rows, the row spacing, the building dimensions and wind direction. Row length was not specifically examined (it was always the full width of the roof) but some conclusions were nonetheless drawn as to its influence for the case of a single row. The model tests were on flat roofs only.

4. FINDINGS

The findings were as follows:

(1) Effect of Collector Angle:-
The two collector angles to the horizontal that were examined were 45° and 60°. It was found that there was little difference between the snow accumulations for these two angles.

(2) Effect of Wind Direction:-

The snow accumulation patterns were found to be very dependent on wind direction. For winds normal to the collector rows the snow tends to accumulate on the downwind side and to a lesser extent on the upwind side of each row. For winds parallel to the rows the solar collectors cause a slight general drop in wind speed over the roof which in turn causes slightly greater retention of snow. For winds approaching the collector rows at an angle the vortices cast off by the ends of the rows help scour snow off the roof but can promote drift accumulations in some areas.

(3) Effect of Wind Speed:-

Until the wind speed exceeds the threshold value for the onset of drifting, snow remains on the roof. Above the onset speed, which is typically 3m/s, snow drifts off the roof and eventually it can become swept clear. Solar collectors tend to retard the flow over some areas of the roof and a greater ambient speed is required before drifting begins. However, a gap between the solar collectors and the roof causes local accelerations of the wind and, if the gap is sufficiently large, the solar collector can actually help keep the roof swept clear.

(4) Single row of Collectors on a Low-rise Roof:-

From the model results, considering the combined effects of different wind directions, it was concluded that snow accumulations are unlikely to exceed those that would occur on the roof without solar collectors if the

following rules are obeyed: the gap between the bottom of the collector and the roof should be set at a value not less than one-sixth of the distance from the collector row to the furthest edge of the roof, this distance being measured perpendicular to the collector row; this rule may be relaxed in cases where it gives a gap size that exceeds one-tenth of the row length; in this last situation the gap can be set equal to one-tenth of the row length. The foregoing rules should prevent excessive snow accumulations in most situations but for small roofs or short collector rows may give a gap size that is too easily blocked by a single heavy snowfall combined with sliding of more snow off the collector. Therefore the gap should never be made smaller than a certain absolute minimum value which is defined in item (8) of this summary.

(5) Single Row of Collectors on a High-rise Roof:-

For high-rise roofs it was found in the model tests that the wind flow separated from the upwind edge creating a large zone of shelter near that edge. In this zone the tests indicated snow accumulates. It is possible that the size of this zone was exaggerated in the model tests compared with full scale. Nonetheless, it is still expected to be present at full scale making it difficult to carry the rules developed for mounting collectors on low-rise buildings over to high-rise buildings with any degree of confidence. A further complication with high-rise roofs, which makes it difficult to arrive at generally applicable rules, is that the wind flow over the roof is strongly

influenced by irregularities in the perimeter of the roof, as viewed in plan, (due to recessed walls for example). However, the model data did indicate that mounting the collector row did close to one edge of the roof was advantageous with the required gap under the collector being similar to that for a low-rise building.

(6) Multiple rows of Collectors on a Low -rise Building:-

For multiple rows of collectors the model results indicated that provided the gap size between the collectors and roof was greater than one-twelfth of the total roof length, measured in the direction perpendicular to the rows, excessive snow accumulation would not occur. For large area roofs this rule leads to gaps that are probably too large to be practical and it becomes difficult to avoid some increase in snow accumulation.

(7) Minimum Gap Set by Snowfall and Slide-off:-

To avoid the gap between the collector rows and the roof being blocked by a heavy snowfall and sliding of the snow off the collectors it is advisable to set an absolute minimum size for the gap. The minimum value should be set according to the severity of snowfall for the region concerned. There is not very much data from which to determine what the minimum gap should be and it is not a quantity that can be determined readily from model testing. However, the following tentative formula is suggested:

$$\text{Minimum Gap} = C_1 D_{24} + C_2 \text{ metres}$$

where D_{24} = maximum 24 hour snowfall depth, in metres, for the region (given for many locations in "Temperature and

Precipitation 1941-1970" by Environment Canada) and C_1 and C_2 are constants. Tentative values for the constants are C_1 = 2.0 and C_2 = 0.5m. If the size of gap given by the rules in item (5) of this summary is higher than given by the above formula, the higher value should be used.

(9) Effect of Parapets:-

Parapets at the roof edge were detrimental to the effectiveness of the gap beneath the collector in keeping the roof clear and it was concluded the gap given by item (5) should be increased by an amount equal to the parapet height if the collector is closer to the roof edge than fifteen parapet heights.

(10) Effect of a Penthouse:-

The influence of a single solar collector row on the snow accumulations around a nearby penthouse was briefly investigated to assess whether unusually high snow accumulations would occur. Generally, the gap beneath the collector caused accelerated flows around the base of a nearby penthouse and it appears unlikely that the presence of the collector would have a large adverse effect on the snow accumulations there.

5. LIMITATIONS

While model tests provide useful insights into snowdrifting phenomena it is not possible for them to fully account for all various facets of snowdrifting behaviour. Thus, uncertainties remain and it is important that the findings form model tests be compared as far as is possible with field observations.

At present there are very few documented field observations with which to compare the present results.

Another limitation concerns the formula for the absolute minimum gap (item (8)) which is intended to take account of the sliding of snow off the collectors. The values for the constant C_1 and C_2 in the formula are not readily determined by model tests and the tentative values given in the report are based on very simplified assumptions. Further investigation is required and it should involve field observations.

PART - II

REPORT

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1. INTRODUCTION

The objective of the study described in this report was to investigate configurations of solar collectors that would minimize snow accumulations. Knowledge of these configurations is useful particularly for installations on existing buildings, where the cost of strengthening the roof to withstand additional snow loads may make the solar collector system as a whole prohibitively expensive.

The factors that have been examined are the effects of collector set-back from the roof edge s, gap beneath the collector g, tilt angle θ, building height H, building width w, building length b, multiple row spacing, diagonal orientation of the collectors relative to the building, and the presence of parapets or a penthouse and wind direction ϕ. The various parameters are defined in Figure 1.

To predict roof snow accumulations by theoretical methods or model tests is a difficult task because the mechanics of accumulation are governed by many different factors, as described by Taylor[1] for example. Snow is deposited in a snowfall and may begin to drift immediately if the wind speed is high, much being swept off the roof, or it may not start to drift until after the snowfall is over. The amount of drifting depends on the type of snow, the wind speed, the wind direction and on the duration for which it blows. If temperature conditions are such that it forms a crust before it has had a chance to drift or if winds are insufficiently strong, then no drifting occurs before the arrival of the next snowfall. The snow may also melt, the degree of melting depending on the temperature and on the heat transfer characteristics of the roof. Thus, the quantity of snow on a roof varies considerably during the winter and the condition of maximum

accumulation also differs considerably from winter to winter. For these reasons the National Building Code (NBC) snow loads are derived by statistical methods and are based on many years of observations of actual snow loads and depths. In most circumstances the net effect of all the various factors on the maximum roof snow accumulation is to make it less than the average ground accumulation and this is reflected in the snow load coefficient C_s being less than unity (0.6 or 0.8) for exposed flat roofs in the NBC. However, in very sheltered regions and on certain types of roof, such as those with a step change in level, C_s may exceed unity.

The most significant effect of free standing solar collectors on roof snow may be expected to be to shelter it from the wind unless special measures are taken to avoid this. Also, certain collector configurations may cause concentrated drifts to form on the roof. Thus, the potential is there for greater snow accumulations to occur than without collectors.

2. LITERATURE REVIEW

There is little in the literature on the accumulation of snow at solar collector sites. In the course of the literature review the following databases and printed indexes were consulted.

- NTIS (1971-September 1980)
- Engineering Index (1970-July 1980)
- Energyline (1971-1980)
- Cold Regions (1962-June 1980)
- Solar Energy Update (1976-1980)
- Energy Abstracts (1976-1980)

In addition information was received from other sources including the Division of Building Research of the National Research Council and the Built Works Technology Group at Public Works Canada.

The most directly relevant reports were the recent ones by O'Rourke[2] and Corotis, Dowding and Russow[3]. The former contains observations on eight installations in New York State, New Hampshire and Connecticut during the first three months of 1979 and the latter contains observations from eighteen sites in the Chicago area in the same winter. An important phenomenon was that multiple rows of free-standing collectors caused a roof that would have been wind-swept in the absence of collectors to become sheltered and retain fallen snow. Collectors could also act like snow fences and initiate drifting. The shelter effect may be reduced by ensuring a gap exists between the bottom edge of the collector and the roof. Another important phenomenon was the sliding of snow off the collectors. This is desirable in that the collector can then continue to operate after a snowfall. To ensure slide-off occurs it is important to minimize obstructions at the bottom of the collector. The gap under the bottom edge of the collector should be large enough that it is not blocked off by the pile of snow formed after slide-off has occurred. The pile formed by the sliding of snow from a large collector, such as one that is flush mounted on a pitched roof, may cause a loading problem it if is deposited on an adjacent flat roof at a lower level. O'Rourke emphasized in his report the need for more data and suggested the use of "controlled prototype and/or model studies" to quantify the effects of collector geometry and wind on snow accumulations.

Three other documents that were obtained were still in draft form. They were a report by Weinstein[4], proposals for design criteria by Harris[5] and proposed guidelines by Nixon[6]. Weinstein's report covers a wide range of architectural topics related to solar collectors. Concerning

snow, he briefly recommends a gap beneath free standing collectors so as to minimize accumulations. Harris' draft design criteria are largely based on the findings of References 2 and 3 which he summarizes. For the structural design of the collectors themselves he recommends use of the basic uniform snow load except where drifts may form on the collector surfaces. For the structural design of the roof he recommends normal loads if the collectors are flush mounted. If the collectors are free-standing he recommends accounting for the shelter effect by incrementing the ANSI roof exposure coefficient C_e by amounts ranging from 0 to 37.5%, depending on the exposure conditions in the absence of the collectors. He also proposed additional local loads due to the sliding surcharge at the collector base. Then drift loads are added if the gap under the collector is less than a critical value of 0.91m (3 ft.) except in areas of heavy snowfall where the gap is required to be greater according to a specific formula containing the ground snow load. Drifting due to a single collector row is supposed to be the same as for a vertical obstruction of the same height and for multiple rows it is supposed to be the same as for a modified saw-tooth roof, the toes of the collectors being the valleys and the tops being the ridges. Harris comments that his design criteria for roof loading are based on very little data and, in view of the increased use of solar collectors that is projected, more work is required.

Nixon's draft guidelines[6] are also tentative in nature. For a roof with free-standing collectors, he suggests using 90% of the ground snow load and he, like Harris, specifies a minimum gap if drifts are to be avoided. His minimum is never less than 1 metre but in some areas his formulae, which contain factors for ground snow load and roof wind exposure, result in larger values. His methods of

accounting for drifting when the gap is below his criterion are similar to those of Harris and he too considers the loading due to sliding surcharge. When a single collector row is short, less than 2.5 times the ground snow depth, he states that drifting need no longer be considered.

Some aspects of the drifting of snow around solar collectors are similar to those for snow fences, on which many papers have been written. Much useful information on snow fences is contained in the paper written in 1950 by Pugh[7]. The blower snow fence, used to sweep rail tracks clear, is similar to a free standing solar collector with the wind blowing at its back side. As with the blower fence, the wind may be expected to accelerate through the gap under the collector and sweep an area clean of snow immediately downwind. However, there are essential differences between the situation of roof mounted collectors and snow fences on the ground. Snow fences normally collect snow from a considerable distance upwind whereas roof mounted solar collectors will generally collect only the snow that fell onto the roof. Ground snow is rarely carried by the wind up to roof height. Thus, unless the roof area upwind is very large there is only a limited supply of snow from which to form drifts and extremely deep drifts of the kind observed around snow fences are unlikely to occur.

3. BASIC APPROACH OF PRESENT WORK

The role of the present model tests was to develop optimum collector configurations that minimize snow accumulations. Thus, in analyzing the data, the emphasis was on looking for configurations that give least shelter to the roof and, if anything, result in greater removal of snow from the roof by wind action than with no collectors. If the roof is

not sheltered and drifts do not form then this removes the most significant cause of increased snow loads due to the presence of collectors.

It should be noted that such an approach does not give the value of the snow load coefficient, C_s, because this coefficient depends on a number of other factors in addition to wind as described in Section 1. With the current state of the art, the most reliable method of predicting C_s, is by analysis of long term field observations. However, an objective of the present study was that some configurations would be arrived at that would not increase C_s over and above the value without solar collectors. Knowledge of such configurations, even with the constraints they impose on the solar collection system, is useful as an alternative to or in lieu of accurate knowledge of C_s, which is unlikely to be obtainable in the short term. As discussed in the introduction, for an existing roof it is arguable that the only data of interest are the configurations that do not increase snow loads since those that do increase snow loads may not be viable in any case due to the expense of having to strengthen the roof.

4. TEST PROCEDURES

A water flume was used to simulate the wind and snow interaction. In the water flume, snow is simulated by fine silica sand and the water flow simulates the wind. Theoretical considerations relevant to this technique are outlined in Appendix A. In addition, wind tunnel tests were carried out in which the wind speed patterns over the roof were measured. In order to ensure realistic flow patterns around the models, the mean velocity profile and turbulence of the wind were simulated by the spire-roughness technique as described in

Appendix B. The approaching wind profile was representative of that in suburban areas.

Since the present tests were essentially comparative in nature, the procedure in the water flume was to subject the models to identical snowfalls followed by identical periods of wind at a fixed speed. The speed was chosen to be sufficient to cause scouring and drifting in the absence of solar collectors but was not so high as to sweep the roof completely clear of snow. The model flow conditions corresponded approximately to a 25cm snowfall followed by 24 hours of wind at roof level mean speeds of 20 and 25 km/hr. respectively for the low and high-rise buildings. The relations between the model wind speed and time and those at full scale are discussed in Appendix A.

The scale of the models in the water flume tests was chosen as 1:200 on the basis that any smaller scale would cause difficulty in maintaining geometric accuracy of such features as the gap between the collector and roof. In addition, it was considered that the gap should be maintained large in comparison to the grains of silica sand (average diameter 0.12mm). A larger scale model was considered undesirable because of blockage effects in the water flume when high-rise buildings were being tested and because it would in principle, have reduced the accuracy of the turbulence simulation. In Appendix A tests are described with different scale models (without solar collectors) and the results were not very sensitive to model scale.

In the wind tunnel tests the scale of the model was 1:50. The measurements consisted of wind speed measurements at a full scale height of 0.2m above the roof surface at twenty-five locations on a 25m by 35m rectangular, flat roof. The speed was measured using

the omnidirectional wind speed sensors described in Reference 8. Check measurements with a hot-wire anemometer agreed well with the wind speed sensors. The wind tunnel tests were again comparative in nature, the objective being to compare the wind speeds over the roof with those in the absence of solar collectors.

5. RESULTS OF WATER FLUME TESTS

5.1 General

Figure 1 defines the geometric variables that were investigated. The tests were confined to flat roofed buildings. The majority of water flume tests were conducted on a 25m square building with a full scale height of 6m but some tests were run on a 30m high building. The value of h for the solar collectors was fixed at 2.4m and their full scale thickness was 16cm. After each run, the patterns of snow accumulation were noted and the snow depths on the roof were measured at a number of locations. Each configuration was tested for four or five wind directions, which, because of the model symmetry, were equivalent to six or eight wind directions respectively. Figure 2 shows a photograph of the water flume model.

5.2 Single Row of Collectors on a Low-rise Roof

Figure 3 shows the snow accumulations for the case without any collectors and Figure 4 shows the case where the collector is positioned in the centre of the roof without a gap, i.e. g = 0. The numbers on the figures show snow depths in units of 0.1 metres. It is noticeable that snow collects adjacent to the solar collector for most wind directions whereas on the unobstructed roof the accumulations occur on different parts of the roof for different wind directions. Thus, over a prolonged period of time, during which the wind may blow from many

directions, the snow on the unobstructed roof would not exhibit a pronounced long term tendency to collect in one spot. Clearly, however, the accumulations with a zero gap solar collector present would have a tendency to continually build up in front of and behind the collector. Furthermore, the test with wind at $\phi = 0^{\circ}$ and 45° indicated a maximum snow depth of 1.2m near to the front face of the collector, considerably above the maximum depth recorded on the unobstructed roof at any one wind angle. Thus, when compared on the basis of a single snowstorm, with winds from only one direction, the zero gap collector is again worse than the no collector case.

In Figures 5 and 6, results are shown for gaps of g = 1m and 2m. The snow accumulations with the 1m gap for some wind directions exceed the maximum obtained on the unobstructed roof but for different wind directions the accumulations now occur in different places and are no longer immediately adjacent to the collector. With the 2m gap the accumulations are moved still further away from the solar collector and, furthermore, are generally smaller in area and no deeper than those on the unobstructed roof. Thus the tests with the collector located in the centre of the 25m long roof indicate that a gap of about two metres will prevent snow accumulations exceeding those that would occur in the absence of a collector.

The preceding results were on a 25m square building. In order to generalize the results to other building planforms, it is worth considering the details of the flow around the solar collector. Figure 7 depicts the flow pattern when the wind is normal to the collector ($\phi = 180^{\circ}$). Behind the collector a low speed wake is formed which spreads out and at a point B downstream it meets the roof

surface. Between the point A below the collector and point B the roof surface will experience wind speeds that are generally higher than or equal to those that would occur in the absence of a collector. In contrast, the roof region downwind of point B will experience a drop in wind speed because of the impingement of the collector wake.

These considerations have significant implications. If it can be ensured that point B lies at the edge of the roof or beyond, then for winds roughly normal to the collector, the snow accumulations on the downwind side will, if anything, be less than on the unobstructed roof. Therefore, the data for the 1m and 2m gaps were examined to determine the distance X_c between points A and B. The point B was identified as the closest point to the collector where the snow accumulation exceeded in depth the results for the unobstructed roof and the resulting values of X_c and X_c/g are given in Table 1. The rule that emerges from Table 1 is that X_c is equal to approximately 7g and this applies for winds both from the front, $\phi = 180^{\circ}$ and the back, $\phi = 0^{\circ}$.

Therefore, the general conclusion is drawn that for winds roughly normal to the collector, the optimum collector position for minimizing the snow accumulation on the downwind side will be in the centre of the roof and the gap, g, should be no smaller than b/14. For example, a building with b = 25m would require a gap of 25/14 = 1.8m. If, for any reason, the collector cannot be mounted in the centre of the roof, then the gap should be increased to equal 1/7 times the distance to the furthest roof edge.

The preceding remarks were concerned with the snow on the downwind side of the solar collector.

When the collector was in the middle of the roof and the wind was normal to it ($\phi = 0^{o}$ or 180^{o}) there was no accumulation upwind of the collector except when g = 0 and even for g = 0 it amounted to only 0.3m. However, when the collector was moved towards the downwind edge of the roof, significant snow depths began to build up on its upwind side. Figure 8 shows examples of this type of accumulation with a 2m gap. It is noteworthy, however, that with the 2m gap the deepest accumulations in Figure 8 only marginally exceeded those on the unobstructed roof, Figure 3.

The physical explanation for snow accumulation upwind of the collector is that the wind decelerates as it approaches the collector. As the gap is increased, however, the severity of the deceleration is decreased.

When the wind flows diagonally across the roof, the flow mechanisms discussed in this section still apply but in a modified form. In addition, the flow is strongly influenced by the complex vortex-like flows that spring from the upwind ends of the solar collector row. However, the depth results for g = 2m in Figure 6 at $\phi = 45^{o}$ and 135^{o} are no greater than those for the unobstructed roof case, Figure 3, so it appears that the corner vortices generated by the end of the collector row tend to help sweep the roof clear for gap sizes greater than 2m.

When the wind flows parallel to the row of collectors ($\phi = 90^{o}$, 270^{o}), Figures 5 and 6, in comparison with Figure 3, indicate that slightly greater buildup of snow occurs with collectors than without, the effect being almost insignificant with the 2m gap. The size of the framework supporting the collector would have a significant influence for this wind direction.

5.3 Effect of Collector Angle

Figure 9 shows results for a collector angle of $\theta = 60^{o}$ for a gap of 2m. These may be compared directly with those in Figure 6 which were for $\theta = 45^{o}$. The results can be seen to be very similar. This was also found to be true in other comparable cases. Table 1 includes results for both $\theta = 45^{o}$ and $\theta = 60^{o}$ and there is no consistent difference that is evident. The remaining results given in this report are for $\theta = 45^{o}$ unless stated otherwise.

5.4 Single Row of Collectors on a High-rise Roof

Figure 10 shows the difference in the shape of the accumulations that occurs on a 30m high building as compared with a 6m high building, Figure 3. The wind speed at the level of the top of the building was faster by a factor of 1.27 for the 30m building than for the 6m building for these tests, but they were both run for the same time, approximately equivalent to 24 hours at full scale. The snow patterns are clearly very different, reflecting the different type of wind flow over the higher building. Despite the greater wind speed at roof level on the high building, the accumulations are of the same order of depth and area as on the low building, indicating that for a given wind speed at roof level, the high-rise roof surface is relatively more sheltered. This local sheltering effect tends to be compensated for by the greater wind speeds that generally exist in the approaching flow at high-rise height. The wind flows over low-rise and high-rise roofs are depicted in Figure 11, with the main difference being that on the high-rise building the flow separates from the windward edge leaving a large region of relatively stagnant air close to the roof surface whereas on a low-rise building the wind flow quickly reattaches to the roof. It is possible that

in the model simulation the extent of the separated flow region on the high-rise building was somewhat exaggerated because of the disparity between the model scale and the simulated planetary boundary layer scale. Nonetheless, the flow separation is still expected to be larger on a high-rise roof. Because of the larger separated flow region, the rules developed for the low-rise roof concerning gap size cannot be carried over with any confidence to the high-rise case.

Figure 12 shows the snow accumulations when a solar collector with a 1m gap is installed at various set-backs from the windward edge of a high-rise roof, the wind direction being θ 180°. The accumulations with the collector centrally located are much greater than with no collector, deep snow building up just behind the collector. The situation improves as the collector is moved closer to the windward edge until, with a 2m setback, the snow depths do not exceed those with no collector. The reasons for this behaviour are considered to be as follows. When the collector is centrally mounted it tends to enlarge the separated flow region, pushing the shear layer emanating from the windward edge further away from the roof, as illustrated in Figure 13(a). The gap is ineffective in this type of flow. As the collector moves closer to the windward edge it increasingly interferes with the shear layer and eventually some of the high speed air outside the separated region gets redirected through the gap, Figure 13(b). When this occurs, snow accumulations are reduced in the immediate vicinity of the collector but, as on the low-rise roof, the impingement of the collector wake tends to increase snow accumulation further downwind.

When the wind direction is reversed to $\phi = 0°$, see Figure 14, and the collector is

centrally located, the snow accumulations near the windward edge of the roof are increased only slightly above those for the unobstructed roof, Figure 10. In contrast to the $\phi = 180^{o}$ case, the gap is effective in clearing snow in the immediate vicinity of the collector. However, the impingement of the collector wake again causes increased accumulation further downwind.

Results were also obtained with a 2m gap and are shown in Figure 13. The case with a setback of s = 2m and with $\phi = 180^{o}$ is interesting in that a substantial region has been swept clear just downwind of the collector indicating the gap has become fully effective for this wind angle and collector position. However, the snow accumulations downwind of the clear region are greater than on the unobstructed roof. The value of X_c, the distance to the wake impingement point, is approximately 5 gap heights rather than the 7 gap heights observed on the low-rise building. When the collector was centrally located the 2m gap was still insufficient to be effective for $\phi = 180^{o}$.

5.5 Multiple Rows of Collectors on a Low-rise Roof

A series of tests on the 6m high building were run with a gap of 1m, with various row spacings and with 2, 3 and 4 rows. A general conclusion was that for the range of spacings tested, 5m to 10m, the snow accumulations would be greater than on the unobstructed roof. The gap effectiveness was reduced on the downwind collectors because of the wakes formed by upwind collectors. The effect of a larger gap size for multiple rows of collectors was explored further in the wind tunnel tests, see section 6.4

Figures 16 and 17 show test results for three rows spaced at 10m intervals and four rows spaced at 5m intervals. A noticeable and unexpected result was

that at $\phi = 90^{\circ}$ accumulations were significantly greater than without solar collectors. At $\phi = 0^{\circ}$ and 180° in Figure 16, the region between the upwind row and the central row is clear of snow but accumulations occur under or just downwind of the central row. At $\phi = 180^{\circ}$ in Figure 17, the roof is clear until the third row downwind is reached and at $\phi = 0^{\circ}$ the accumulation at the downwind end of the roof is significantly deeper than on the bare roof, Figure 3.

5.6 Influence of Parapets

The presence of a parapet upwind of a solar collector decreased the effectiveness of the gap between the solar collector and the roof. Figures 18(a) through (d) illustrate this effect for $\phi = 180^{\circ}$.

In Figures 18(a) and (b) the change in snow accumulations due to adding a 1m parapet to the roof is shown. In Figures 18(c) and (d) the accumulations around a collector, with 1m gap and 6m setback, are shown for 1m and 0.5m parapets. Even with the 0.5m parapet where the solar collector was twelve parapet heights downwind, the accumulations built up just behind the solar collector indicating the gap was not fully effective. Thus, the influence of a parapet extends many parapet heights downwind. In view of this, an increase in gap appears warranted when a parapet is present. In lieu of entering into an exhaustive study of this particular item, a reasonable first assumption would be that when a parapet is present, the gap size should be incremented by an amount equal to the parapet height if the collector is within 15 parapet heights of the roof edge.

5.7 Diagonal Orientation

Tests with a single collector row positioned on the diagonal of the 6m high building with a gap of 1m showed greater accumulations than without a collector. Figure 19 shows results for a gap of 1m. At $\phi = 135^{o}$ the accumulation in the downwind corner region of the roof is attributed to the wake impingement effect described in Section 5.2, and the distance downwind of the collector that this occurred was approximately 8m, just beyond the 7 gap heights. Thus, it appears that the criterion developed in Section 5.2, that the gap be greater than 1/7 of the distance to the furthest roof edge, still holds approximately for the diagonally oriented collector on a low-rise building.

5.8 Effect of a Penthouse

Tests were conducted with a penthouse, 5.5m x 9.5m in plan and 2m high, centrally located. Various positions of a 2m gap collector on the south side of the penthouse were examined. It was found that as the collector approached the penthouse it helped accelerate the flows in the vicinity of the penthouse and thus reduced accumulations. Figure 20 shows accumulations with the collector so close as to actually be overhanging the penthouse. Ultimately, if the collector touches the edge of the penthouse the gap would not be expected to function properly. Thus, it would be advisable to leave some clearance and value of one gap height clearance between the edge of the penthouse roof and the collector would appear reasonable.

5.9 Cumulative Effect of Different Wind Directions

The approach in the preceding sections was to examine each wind direction separately and to note locations where significant accumulations occurred for one or more wind directions. However, it is desirable, in addition to have some quantitative

measure of the cumulative effect of winds from all directions. The simplest approach is simply to add the accumulations for the eight wind directions covered by the tests and this was done for the single collector mounted centrally on the roof with various gap sizes.

The roof area was broken into a 6 x 6 grid pattern and for each wind direction an average snow depth was assigned to each grid square based on the water flume tests. Then the average depths were summed over the eight wind directions, ϕ = 0, 45, 90, 135, 180, 225, 270 and 315 degrees. The accumulated snow depths thus calculated for each grid square are illustrated in Figure 21 for the 6m high building with a centrally located collector with various gap sizes. Also shown are results without the collector.

The above procedure provides a basis for comparison which includes in a simplified way the effects of different wind directions. In Figure 21, taking the case without the collector as the datum, it is clear that gaps of 0m or 1m produce higher overall accumulations but that the 2m gap produces lower accumulations. This conclusion agrees with what was found earlier by examining results for each wind direction individually.

This approach was not pursued further in the present study since it entailed extensive analysis of the data and it was felt the available resources would be better directed towards wind tunnel tests to complement the water flume tests and to explore additional configurations.

5.10 Effect of Wind Speed

The wind speed simulated in the water flume was the same for the majority of the tests, i.e. 20km/hr

at roof height in the low-rise tests and 25 km/hr in the high-risetests. Some runs at slightly lower speed did result in accumulations building up closer to the solar collector than at the higher speed. The cause for this was considered to be that in a narrow range of speeds near to the threshold at which snow begins to be moved by the wind, the accelerated flow under the collector scours the snow from that area but, because the deceleration behind the collector soon drops the speed to below the threshold level again, the snow does not travel far before settling back on the roof. This phenomenon has the potential to cause local increases in accumulation on the roof closer to the collector than at higher speeds. However, the range of wind speeds involved is fairly narrow and the probability of the speed remaining in this range and from the critical direction for a long period, is small.

6. RESULTS OF WIND TUNNEL TESTS

6.1 General

The roof planform for the wind tunnel tests of a 1:50 scale model was a 25m by 35m rectangle. The majority of the tests were on a 6m high building but results were also obtained on a 20m high building. Figure 22 shows a photograph of the model on which may be seen the locations of the wind speed sensors which measured the speed, U, at a height equivalent at full scale to 0.20m above the roof surface. The mean speed and the peak or gust speed were recorded and were divided by a reference mean wind speed, U_o, measured at a height of 36m. The resulting speed ratios were used as a basis for comparing the various solar collector configurations. The symbol, x, is used to denote distance from the south edge of the roof.

6.2 Single Solar Collector on a Low-rise Roof

Figures 23(a) and (b) show the wind speed variation along the centre of the roof for $\phi = 180^{\circ}$ and 0° with a collector row mounted midway along the roof. The vertical scale is the ratio of local speed, U, to the reference speed, U_o, at the reference height of 36m and the horizontal scale is the distance from the south edge of the roof. The results in Figure 23, which include data for the bare roof, corroborate the picture of the wind flow in Figure 7. Immediately downwind of the collector there is an accelerated flow region, the extent of which increases with gap size. Just upwind there is a decelerated zone. The zone of accelerated peak speed is longer than that for the mean speed for the configurations shown. Snow transport tends to be determined more by the peak speed than the mean. The zone of accelerated peak speeds is between 5 and 6 gap heights in extent, compared with the 7 gap heights deduced from the water flume tests.

Further plots of the wind speed distribution for $\phi = 180^{\circ}$ are shown in Figure 24(a). In this case the collector had been moved to within 2m of the south edge of the roof and gaps of up to 4m were tested. With the 4m gap the zone of accelerated flow extended as far as 20m behind the collector row and, beyond that, the drop in wind speed, compared with that with no collector, was relatively minor. With the 0.5m gap, the smallest tested, the peak wind speed eventually recovered and reattained the bare roof value at a distance of approximately 25 metres behind the collector. However, the mean speed remained very low. Figure 24(b) shows a plot of X_c/g versus the gap height, g, where X_c is the previously defined length of the zone of accelerated wind. It can be seen that the conclusion from the flume tests, where the evaluation of X_c was more

indirect, that $X_c/g = 7$ for all situations, was somewhat simplified compared with the wind tunnel data, Figure 24(b), which show some dependence of X_c/g on the value of g, the wind direction ϕ , and on the setback, s. The lowest value of X_c/g was about 5, and it ranged as high as 9 for the 0.5m gap, with $\phi = 180^o$ and S = 2m. However, it is desirable to retain the simplicity of a single representative value for X_c/g and, in this regard, the wind tunnel data indicate that for gaps in the 1m to 3m range a value of $X_c/g = 6$ is more representative than 7. Thus, the value of 6 is adopted henceforth.

The preceding discussion has concentrated on the wind flow normal to the collector row, $\phi = 180^o$ and 0^o. For other wind directions areas that are sheltered for $\phi = 180^o$ or 0^o become exposed. The further away the sheltered zone is from the collector, the more quickly does it become exposed as the wind direction moves away from 180^o or 0^o. Thus, one effect of a larger gap is that, in pushing the sheltered zone away from the collector row, it enables the beneficial effects of changing wind directions to come more into play.

The effect of changing wind directions in exposing the zones of shelter that exist at $\phi = 0^o$ or 180^o, is to a large extent governed by the length of the collector row, which, in the present work was equal to the building width, w. Thus the ratio g/w is important as well as the parameter g/b already introduced. From the flume tests, it was deduced that g should be approximately b/14 for a centrally mounted collector row. Based on the wind tunnel tests this should be increased to b/12 (because X_c/g is now taken as 6 rather than 7). Clearly, for very large values of b this rule would lead to impractibaly large gaps. However, once the

point of wake impingement, with its shelter zone, reaches a distance of order w away from the collector row it is reasonable to assume the beneficial effects of changing wind directions become important. Furthermore, the deficit in wind speed becomes less as the sheltered zone moves far downwind of the collector. These considerations lead to the idea of an upper limit g_{max} for the gap height given by

$$g_{max} = \text{constant} \times w$$

To determine an appropriate value for the constant in this expression is not straightforward because it depends on the wind and snow climate which varies depending on location. However, a tentative value for the constant of 1/10 is suggested as being in the right range.

Figure 25 shows the ratio of peak speed with a collector, averaged over the wind directions $\phi = 0^{o}$, 45^{o}, 90^{o}, 135^{o} and 180^{o}, to that without a collector at the twenty five measurement locations on the roof. There is some scatter in the results but it can be seen that with a 1m gap there is a region about 7m north of the collector row where the ratio of angle-averaged peak speeds falls below 0.90 whereas with a 2m gap the ratio remains above 0.95 over the entire roof except for a single 0.93 value near the south edge. The w/10 rule for g_{max} would give g = 2.5m which, based on the 1m and 2m gap results, would be sufficient to prevent significant speed deficits on the roof.

6.3 Single Collector Row on a High-rise Roof

To represent a high-rise building the height was increased to 20m, which was about the maximum that could be simulated at 1:50 scale in the wind tunnel. Figure 26(a) shows the effect of increasing the gap of a single collector row set back 2m for the

wind direction $\phi = 180^{o}$. The wind speeds shown are those along the centre of the roof. With a 3m gap it can be seen that the peak speed is greater than with no collectors for a distance of 16m downwind. This distance decreases to 10m and 4m respectively for 2m and 1m gaps. With the 1m gap there is evidence of some recovery of wind speed at the downwind end of the roof. When the wind was reversed to $\phi = 0^{o}$ the peak speeds on the roof were similar to those with no collectors.

Figure 26(b) shows comparable results for gaps of 2m, 3m and 4m when the setback is increased to 10m. It can be seen that the increased setback decreases the effectiveness of the 2m gap considerably. The mean speed in particular is affected. The 3m and 4m gaps do however maintain an excess of wind speed for significant distances downwind and also upwind of the collector row.

For high-rise buildings it is logical to expect the parameters, g/H, s/H and w/H to have an influence. To fully explore the effects of these parameters would require additional tests in which they were systematically varied more extensively than was possible in the present work. At the present stage it does not appear possible to arrive at simple rules for the high-rise on as certain a basis as for the low-rise case. However, the present results indicate that there is a benefit in positioning the collector close to the roof edge, within approximately one gap height. For this position there is an accelerated flow region extending about five or six gap heights downwind. Thus, including the setback, a roof with b equal to six or seven gap heights would be kept clearer of snow than with no collector. For definiteness it is suggested the criterion $g > b/7$ be used with an upper limit of $g = w/10$ being set by the row length.

On high-rise buildings irregularities in the building planform such as recessed segments of the walls create significant changes in the flow over the roof. This was evident in tests on a Scarborough apartment building where increased scouring of snow was caused by vortices originating at recesses in the planform. As a result a smaller gap was justifiable in that case than for a more regular planform.

6.4 Multiple Rows of Solar Collectors on a Low-rise Roof

In the water flume tests (Section 5.5) it was found that multiple rows of collectors generally increased snow accumulations. Those results were with a 1m gap. In the wind tunnel larger gaps were investigated. Figure 27(a) shows the peak and mean wind speed distributions along the centre of the roof for $\phi = 180^{\circ}$ with several gap sizes. The row spacing was 5m for the results shown. It can be seen that the 1m gap was insufficient to prevent a substantial drop in peak wind speed, compared with that on the bare roof, starting just downwind of the second row of collectors. With the 2m gap the main drop in wind speed was postponed until beyond the fourth row. With the 3m gap the drop in peak speed did not occur until beyond the fifth and last row. The horizontal distance over which the accelerated zone extended was in the range of six to eight gap heights. This is similar to the range for the single collector. With the reverse wind direction, $\phi = 0^{\circ}$, the drop in peak speed was not as dramatic with the 1m gap. The 3m gap was again sufficient to maintain an excess of speed under the whole five rows. The preceding results are for the central lane of the roof. Towards the edges the speeds are higher than in the central lane because of vortices originating at the upwind corners.

In addition to 5m row spacing, 7.5 and 10m spacings were tested. The results were generally similar to the 5m case at $\phi = 180^{\circ}$ and 0° in that an accelerated flow region extended for six to eight gap heights downwind of the most upwind collector.

For $\phi = 90^{\circ}$ the peak speeds with multiple rows of collectors were significantly reduced compared with the bare roof. This is consistent with the finding in the water flume tests that significant increases in snow accumulations occurred for this direction. The reduction in wind speed is illustrated in Figures 28(a) and (b) which show the plan view of the roof, annotated with peak ratios with and without collectors for $\phi = 90^{\circ}$.

Table II gives the peak speed ratio averaged over the whole roof area for various gaps, spacings and wind directions. It can be seen that increasing the gap to as high as 3m does not prevent a significant drop in the peak speed ratio at $\phi = 90^{\circ}$. However, for most other wind directions increasing the gap size is a significant benefit.

The peak speed ratios in Table II, which have already been averaged over the roof area, may be further averaged over wind direction. The values were averaged over directions $\phi = 0^{\circ}$, 45°, 90°, 135° and 180° and are shown plotted in Figure 29 versus gap size for the three different row spacings (the curve for 10m is partly conjectural because only the 2m gap was tested). The plot indicates that for the peak speeds on this 25m by 35m roof to exceed on average those on the bare roof a gap of between 2.5 and 3.0m is required. The form of averaging used here gives results that would be

representative for a site where the wind blows generally from either the east or west half of the compass range. Slightly different results would be obtained for other types of wind frequency distribution.

The general conclusions that may be drawn from the multiple row tests on a low-rise building are that significant drops in wind speed on the roof below the collector array do not occur for on the order of seven gap heights downwind of the start of the array. For an array covering a roof this would lead to a gap of b/7. However, some drop is tolerable since accumulations of snow in a low speed area would tend to get removed when the wind changes to another direction.

Figure 29 gives some guidance as to the overall effect of different wind directions. For the 35m long roof, a gap of between 2.5m and 3.0m, depending on row spacing, sufficed to raise the average value of the peak speed on the roof to above the bare roof value. This corresponds to a gap in the range of b/12 to b/14, rather than the b/7 value deduced for winds confined to the direction normal to the collector rows. The value g = b/7 is conservative since winds are not in reality confined narrow sectors for extended periods. The range b/12 to b/14 is more representative for winds from varying directions. From these considerations it is suggested that the gap criterion g >b/12 is reasonable for multiple rows covering a roof.

6.5 Effects of Parapets

Figure 30(a) shows the influence of a 1m high parapet on the peak speed distribution along the centre part of the roof for $\phi = 180^{\circ}$. The region of accelerated peak speeds behind the collector can be seen to be no more than about 6m in extent even

for the setback s = 8m whereas with no parapet it would have been approximately 6 gap heights, i.e. 12m, (see Section 6.2). This reinforces the finding of the water flume tests that the effect of a parapet extends a considerable distance downwind.

Figure 30(b) shows the peak speed distribution with four rows of 2m gap solar collectors spaced at 7.5m intervals with a 1m parapet present. Clearly the wind speed near the roof surface is greatly decreased and increased snow accumulations would occur for such an arrangement.

7. MINIMUM GAP SET BY SNOWFALL AND SLIDEOFF

The model tests have highlighted the importance of the gap under the solar collector. Clearly the gap should be large enough that it does not become blocked by the combined contributions of heavy snowfall in light winds and snow sliding off the collector to form a pile at its base. If there is a gap still left after a snowfall and sliding the wind will still be able to scour snow from under the collector and thus tend to clear the gap again provided an ice crust has not formed. To avoid the gap becoming blocked it is necessary to specify an absolute minimum value for g which will be denoted by g_{min}. To determine an appropriate value for g_{min} is a complex problem since it requires examining the probability of several different processes (heavy snowfall, light winds, ice crusting) occurring jointly and this would constitute an extensive study in itself.

A simple approach to the problem in lieu of a more detailed study, is to take the deepest recorded 24 hour snowfall for the location in question (such information is available in Reference 9 for a variety of locations in Canada), multiply it by a factor C_1 to allow for sliding off and previous accumulation,

and then to add on a further amount, say C_2 metres, to ensure a gap still exists. Thus, the expression for g_{min} becomes

$$g_{min} = C_1 D_{24} + C_2 \text{ metres}$$

where D_{24} is the depth of the greatest 24 hour snowfall in metres. The values for C_1 and C_2 of 2.0 and 0.5m respectively are suggested. Since there is little concrete information to go on at present these values are very tentative.

The foregoing approach is straightforward but the problem is in reality very complex, and further investigation is warranted. In particular the values of C_1 and C_2 require refinement.

8. CONCLUSIONS

8.1 General Comments

Before discussing specific conclusions it should be stated that they are based on model tests of a limited number of configurations of buildings and collectors. Clearly, for very different configurations they may not be applicable. It is therefore important to employ a degree of judgement in applying the results of this study to any particular installation.

Another point that should be made is that the findings of this study relate to configurations that will not increase snowloads above the bare roof case. The size of gap required to achieve this may often turn out to be considerably larger than has conventionally been employed and may be so large as to make the collector system uneconomical to install or may raise wind loads to unacceptable levels. A large gap also has aesthetic implications. It has not been the purpose of the present study to address the economics, wind loads or aesthetics of solar collector systems but rather to determine what is

actually required from the point of view of avoiding snowload increases. (The problem of wind loads is being addressed in a separate study by the authors of this report, funded by the National Research Council).

8.2 Low-rise Roofs

(i) Single Row of Collectors:

For a single row of collectors on a low-rise roof the recommended gap size is summarized in Figure 31 which shows the gap, g, plotted against the distance, c, measured normal to the collector row, from the collector row to the furthest roof edge. The absolute minimum gap is determined by the maximum recorded 24 hour snowfall D_{24}, in metres for the location and is given by

$$g_{min} = C_1 D_{24} + C_2 \text{ metres} \qquad (A)$$

Tentative values for C_1 and C_2 are $C_1 = 2.0$ and C_2 0.5m.

The value of the depth, D_{24}, of the maximum 24 hour snowfall is given in Reference (9) for a large number of locations. When c exceeds six times the value of g given by Equation A then the following relation should be used

$$g = c/6 \qquad (B)$$

Note that, according to Equation B, g may be minimized by locating the collector centrally at which point c is at its minimum value of 0.5b. For short collector rows the wind is more able to scour away the snow from behind the collector when it changes direction. To reflect this, the gap size may be reduced to w/10, where w = row length, if w/10 is less than c/6. However, g should still not be allowed to fall below g_{min} as determined by Equation A.

(ii) Multiple Rows of Collectors:

For multiple rows of collectors covering a roof the absolute lower limit to the gap is still set by Equation A. However, the gap should also be not less than b/12, which is a more stringent requirement except at small values of b. For multiple rows covering a roof it does not appear justifiable to have an upper limit of g based on row length.

(iii) Effects of Parapets:

The influence of parapets is felt many parapet heights downwind. If a collector is within 15 parapet heights of the roof edge the gap should be incremented by an amount equal to the parapet height.

(iv) Effect of a Penthouse:

The model results indicated that mounting a solar collector close to a penthouse does not adversely affect snow accumulation around the penthouse. However, it would appear advisable to maintain a clearance of approximately one gap height between the penthouse roof edge and the collector.

8.3 High-rise Roofs

General conclusions for solar collectors on high-rise roofs are more difficult to arrive at then for low-rise roofs because of the additional variable, H, and because it is probable that the building width w becomes important. It is worth noting, in this connection, that the national Building Code does not differentiate between low and high-rise roofs when specifying the snow load coefficient. The fact that the wind flows are different for the high-rise case indicates that some differentiation would be appropriate. Wind speeds are generally greater at the height of the high-rise roof which would lead to the expectation of greater removal of snow. However, the larger region of

separated flow reduces the effectiveness of the wind so the net effect is left uncertain. The size of the separated region would be sensitive to the building shape.

Insufficient data were obtained in the present tests to fully determine the optimum locations and gaps for solar collectors that will not increase snow accumulations on high buildings. However, the data indicated that when considering a single row a good location is within one gap height of the roof edge where the separated flow region is not very thick. A tentative guide to g is then that it be at least b/7 unless this makes it greater than w/10, in which case it should be set to g = w/10. In any event the gap should not be less than that given by Equation A, Section 8.2. For positions further towards the roof centre the effectiveness of the gap is greatly impared. Another factor to be borne in mind is the beneficial effect of irregularities in the roof planform. Model tests on a high-rise Scarborough apartment building, which in plan view had segments of its walls recessed showed increased scouring due to vortices originating at the corners of each recess. These vortices substantially modified the wind flow past the solar collector and a gap smaller than the above tentative guide was recommended for that case.

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TABLE 1

	S,m	g,m	ϕ,Deg.	X_c,m	X_c/g
$\theta = 45^\circ$	12.5	2	180	12.5+	6.2+
	12.5	2	0	12.5+	6.2+
	12.5	1	180	7.3	7.3
	12.5	1	0	6.9	6.9
	6	2	180	14.6	7.3
	6	1	180	8.4	8.4
	6	1	0	6.0+	6.0+
	4	2	180	14.5	7.2
	4	1	180	8.0	8.0
	2	2	180	15.9	8.0
	2	1	180	10.0	10.0
				Average =	7.4+
$\theta = 60^\circ$	12.5	2	180	12.5+	6.2+
	12.5	2	0	12.5+	6.2+
	12.5	1	180	5.4	5.4
	12.5	1	0	7.7	7.7
	6	2	180	13.8	6.9
	6	1	180	7.9	7.9
	6	1	0	6.0+	6.0+
	4	2	180	13.9	7.0
	4	1	180	6.7	6.7
	2	2	180	15.9	8.0
	2	1	180	9.9	9.9
				Average =	7.0+

DISTANCE, X_c, TO POINT OF WAKE IMPINGEMENT

TABLE II

Configuration	Wind Direction, ϕ, deg.	Gap, m 0.5	1.0	2.0	3.0	(no collectors)
5 rows,	0	0.75	0.75	0.88	0.89	0.84
spacing = 5m	45	0.82	0.84	0.85	0.92	0.92
setback of	90	0.75	0.76	0.74	0.73	0.84
south row	135	0.85	0.83	0.87	0.93	0.95
= 2m	180	0.64	0.68	0.81	0.95	0.86
4 rows,	0	0.80	0.80	0.82	0.92	0.84
spacing = 7.5m,	45	0.92	0.89	0.94	0.94	0.92
setback of	90	0.79	0.75	0.77	0.78	0.84
south row	135	0.85	0.89	0.89	0.91	0.95
= 2m	180	0.70	0.73	0.81	0.92	0.86
3 rows,	0	-	-	0.83	-	0.84
spacing =10m,	45	-	-	0.93	-	0.92
setback of	90	-	-	0.79	-	0.84
south row	135	-	-	0.93	-	0.95
= 2m	180	-	-	0.82	-	0.86

PEAK SPEED RATIOS AVERAGED OVER THE AREA OF A 25m x 35m ROOF WITH MULTIPLE ROWS OF COLLECTORS

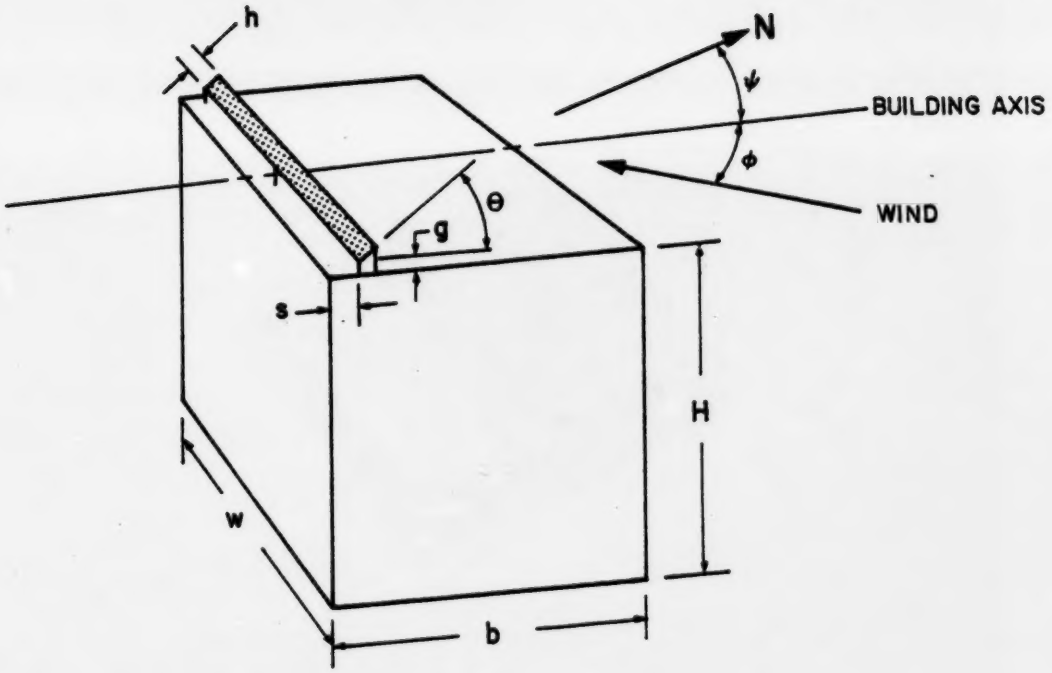


FIGURE 1
DEFINITION OF PARAMETERS FOR SINGLE COLLECTOR

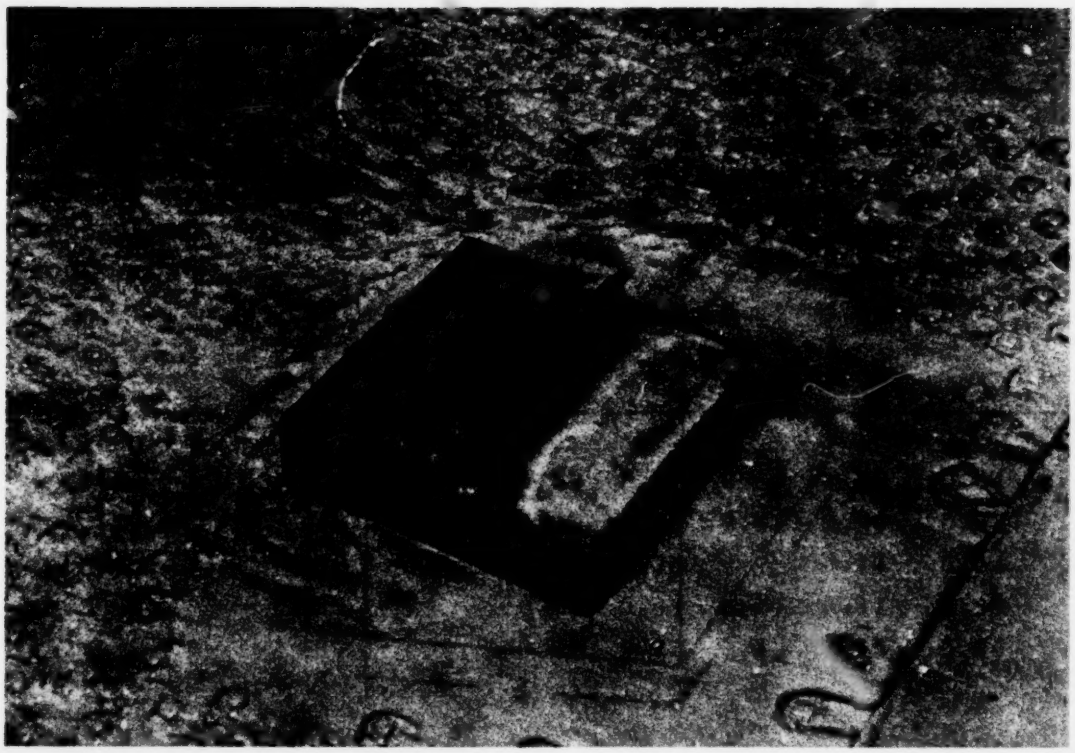


FIGURE 2
WATER FLUME MODEL OF 25m x 25m LOW-RISE BUILDING

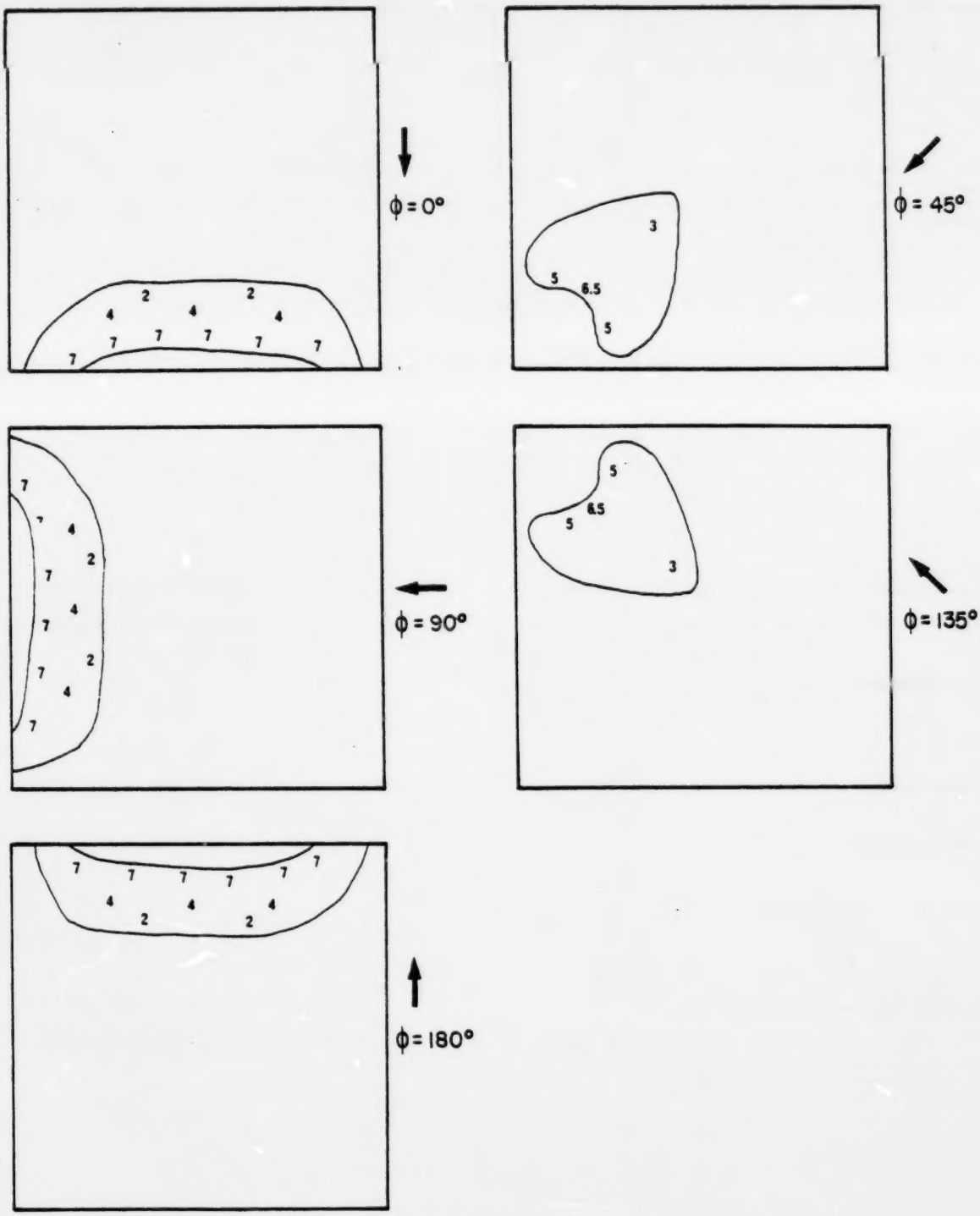


FIGURE 3

SNOW ACCUMULATION ON A LOW-RISE ROOF

H = 6m

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

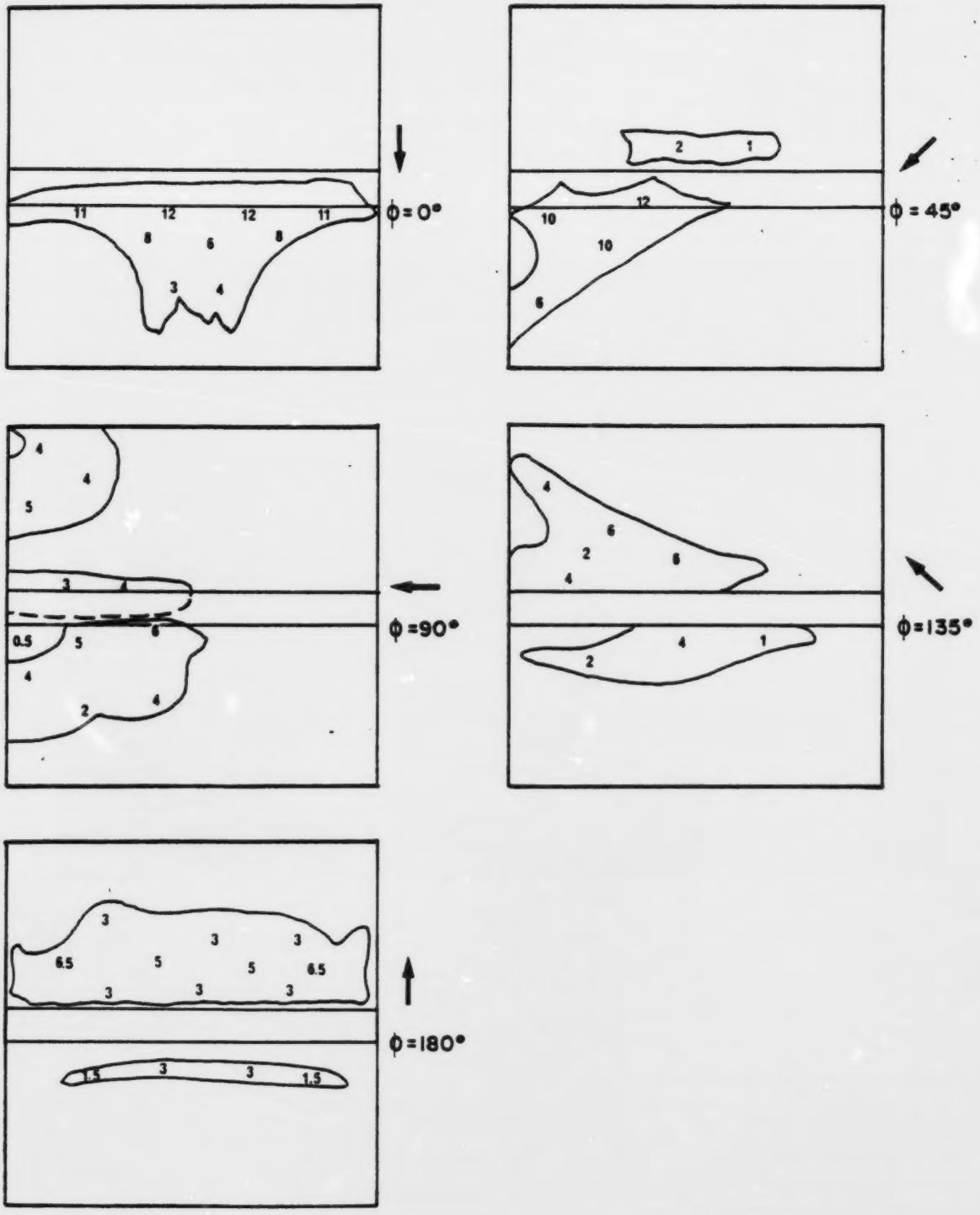


FIGURE 4

SNOW ACCUMULATION ON A LOW-RISE ROOF

H=6m, g=0m, θ=45°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

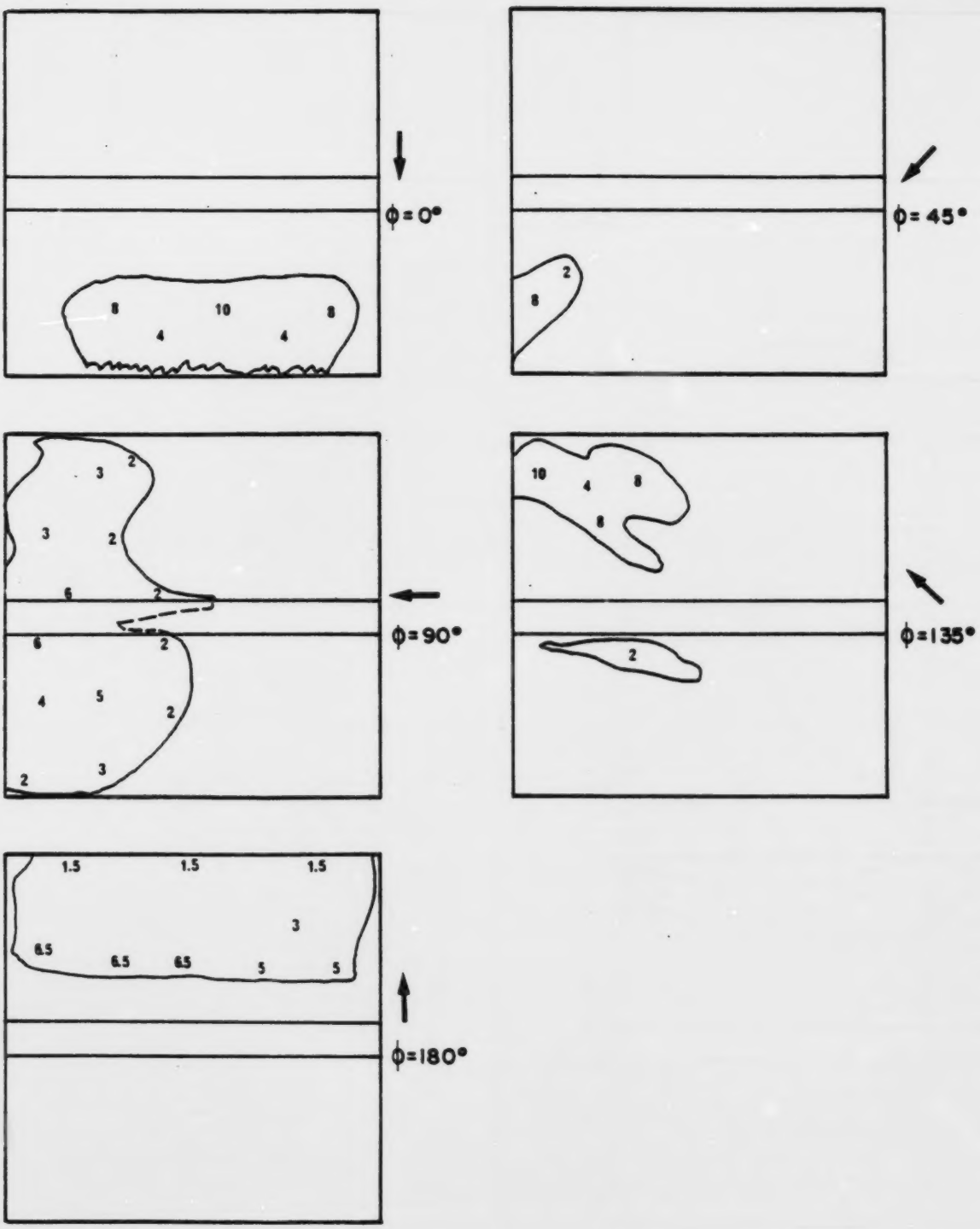


FIGURE 5

SNOW ACCUMULATION ON A LOW-RISE ROOF

H=6m, g=1m, θ=45°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

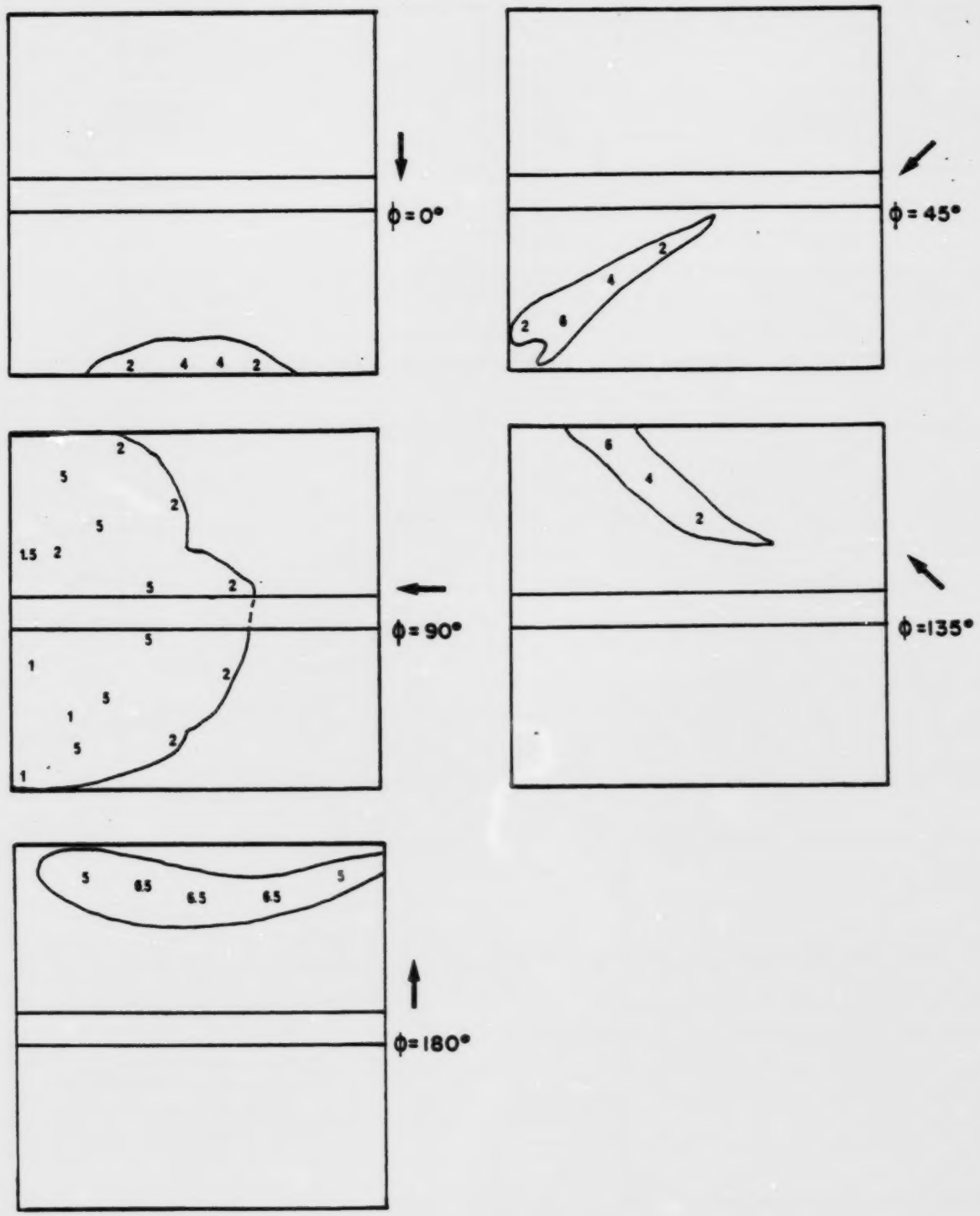


FIGURE 6

SNOW ACCUMULATION ON A LOW-RISE ROOF

H= 6m, g=2m, θ=45°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

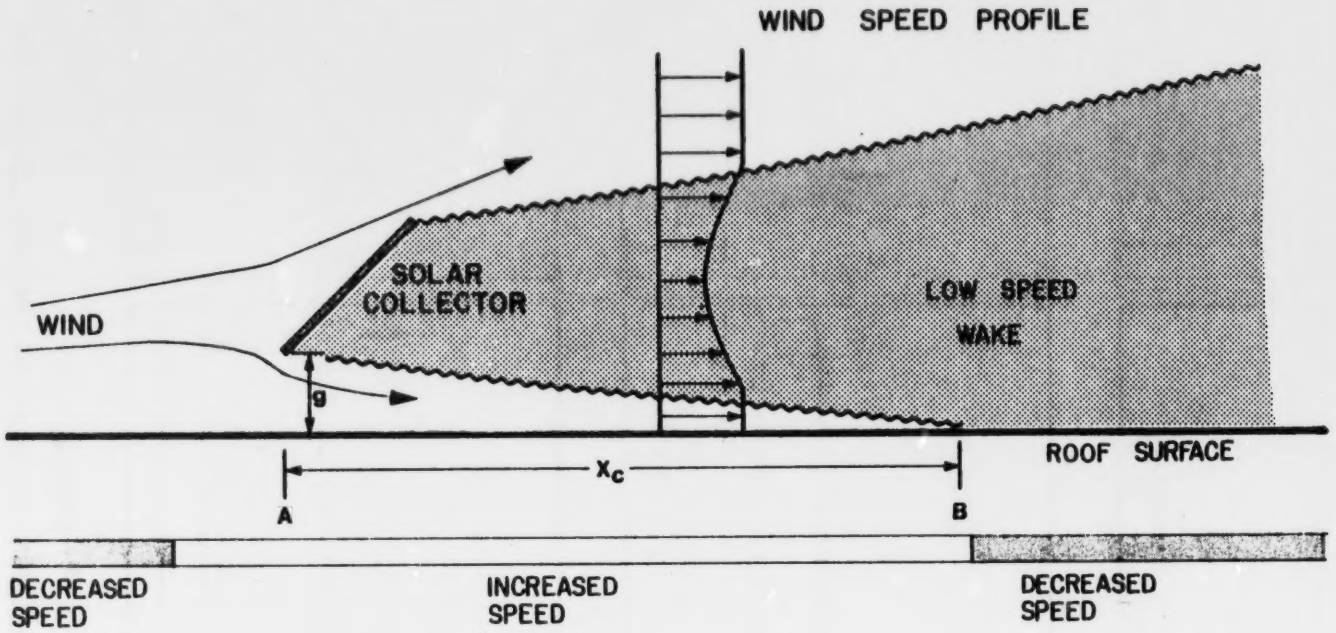


FIGURE 7

WIND FLOW AROUND A SOLAR COLLECTOR

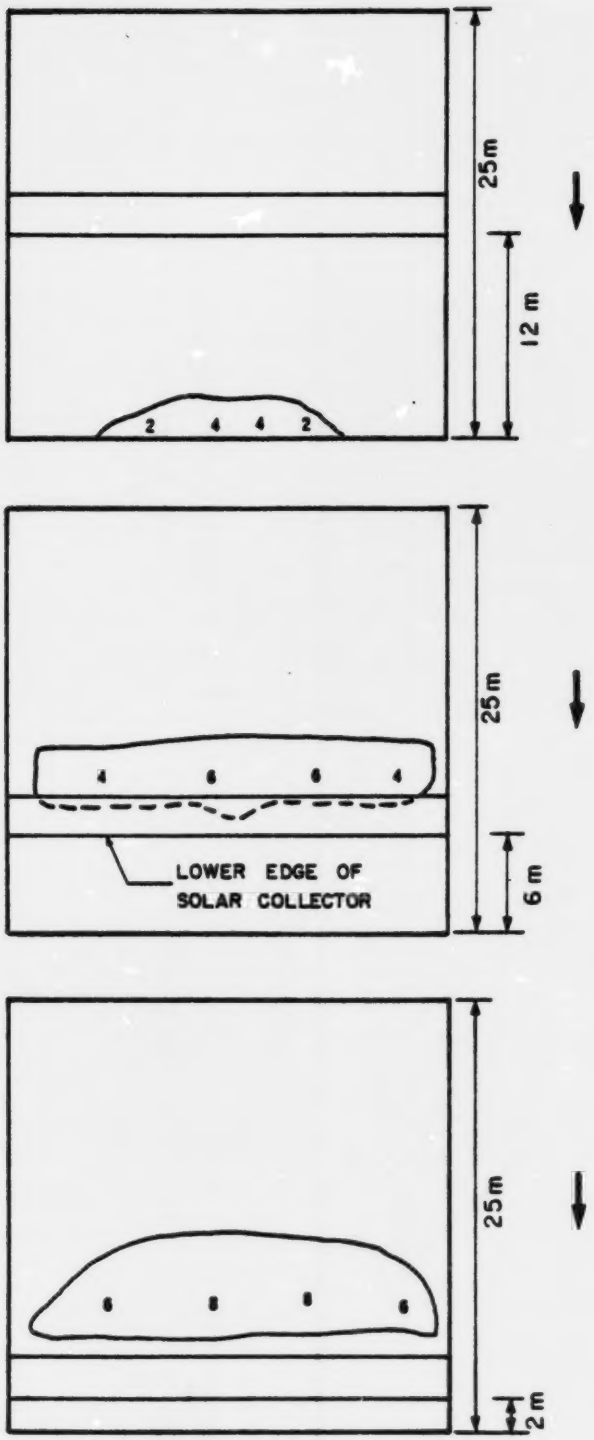


FIGURE 8

SNOW ACCUMULATION UPWIND OF SOLAR COLLECTOR
H=6m, g=2m, θ=45°, ϕ=0°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

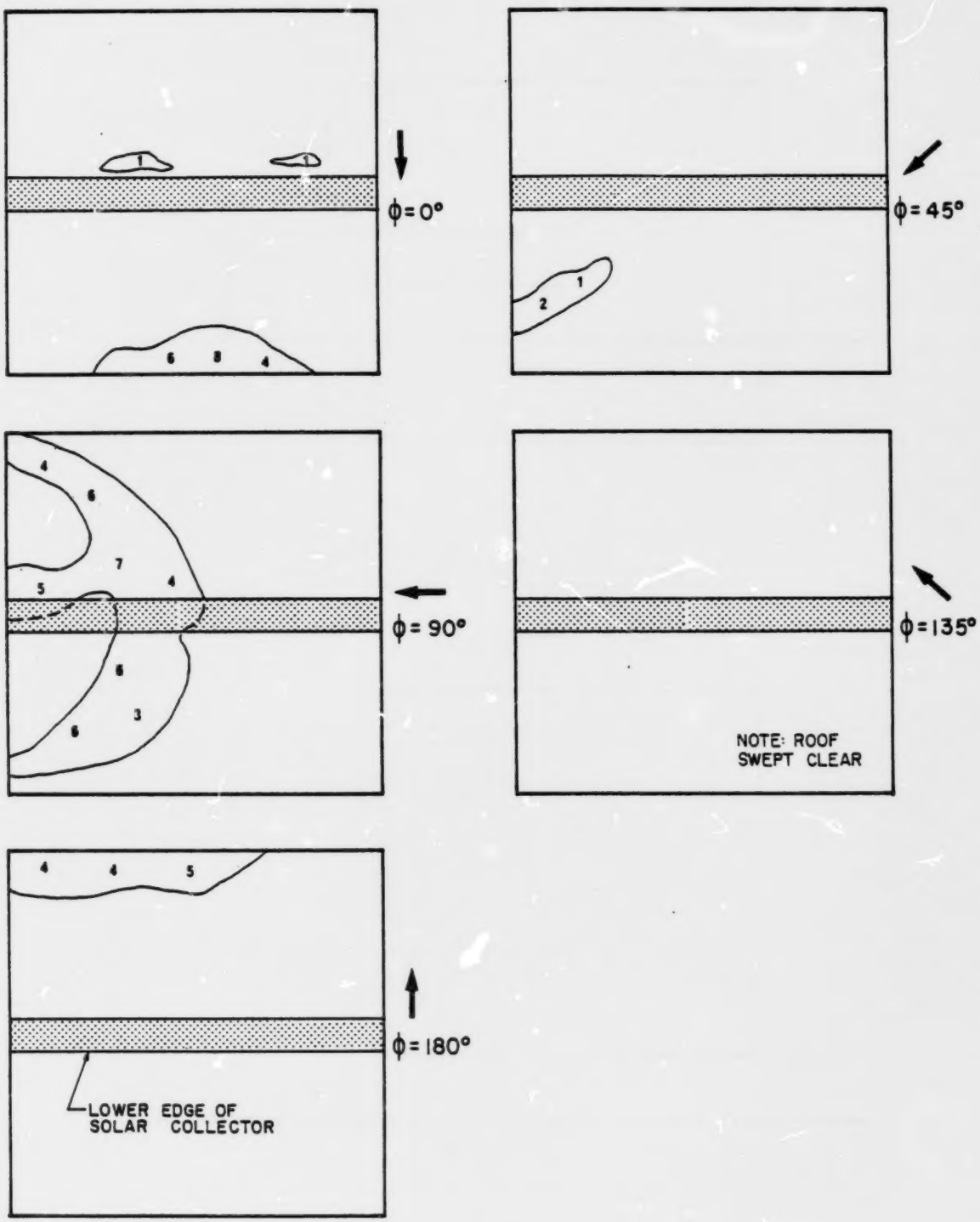
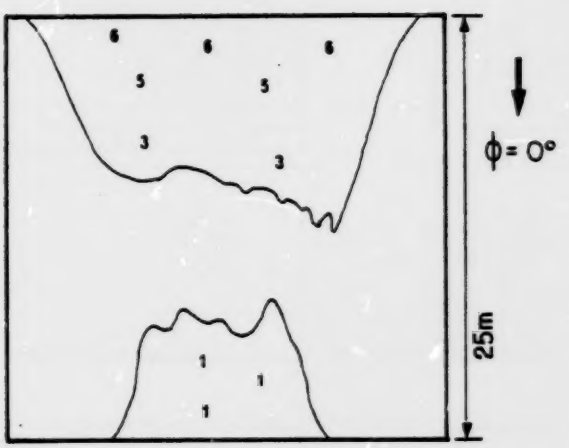


FIGURE 9

SNOW ACCUMULATION ON A LOW-RISE ROOF

H=6m, g=2m, θ=60°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS



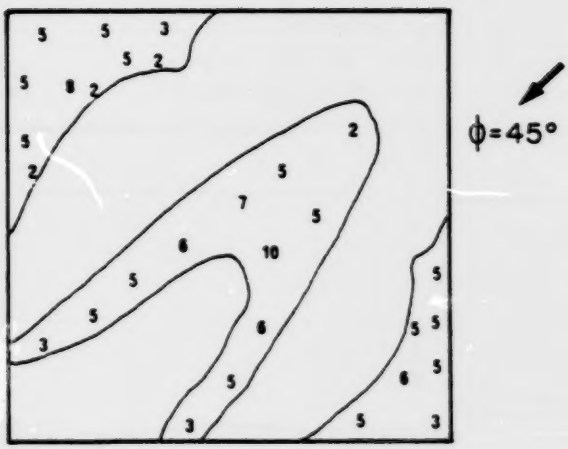
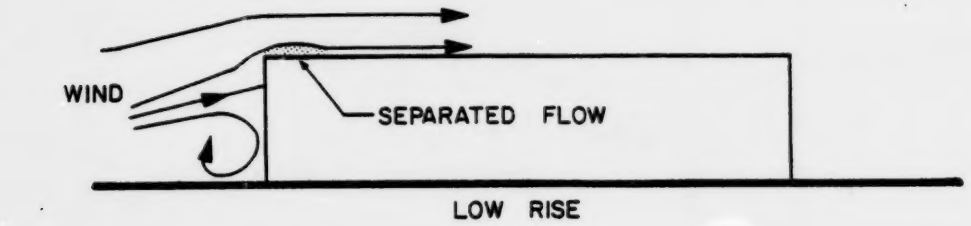


FIGURE 10

SNOW ACCUMULATION ON A HIGH-RISE ROOF

H = 30m

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS



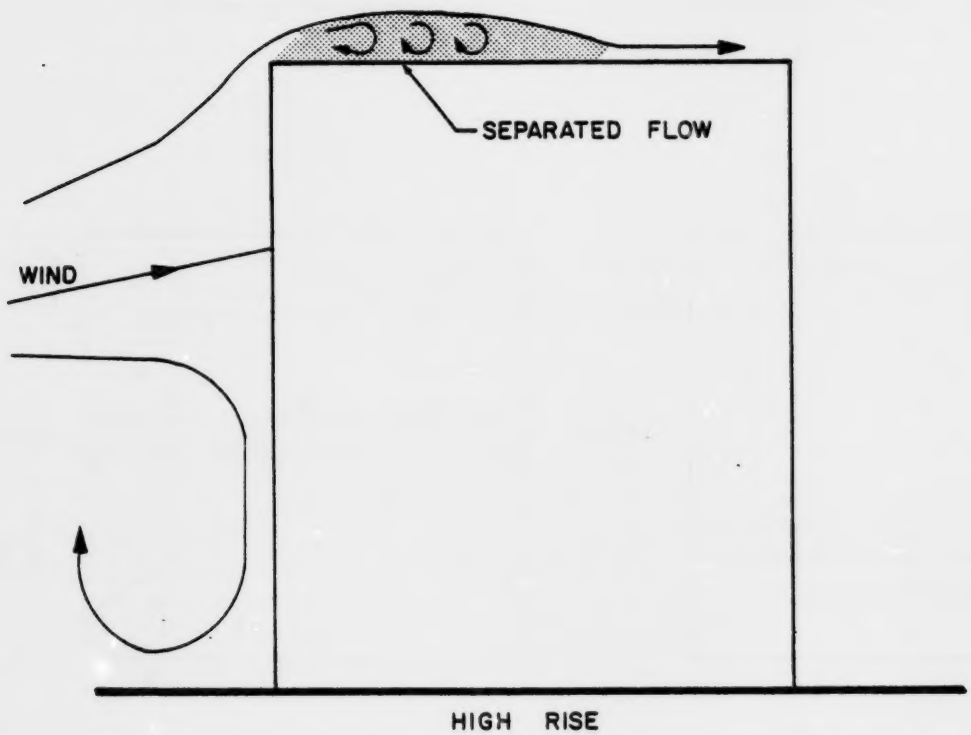


FIGURE II
WIND FLOW SEPARATION FROM ROOF

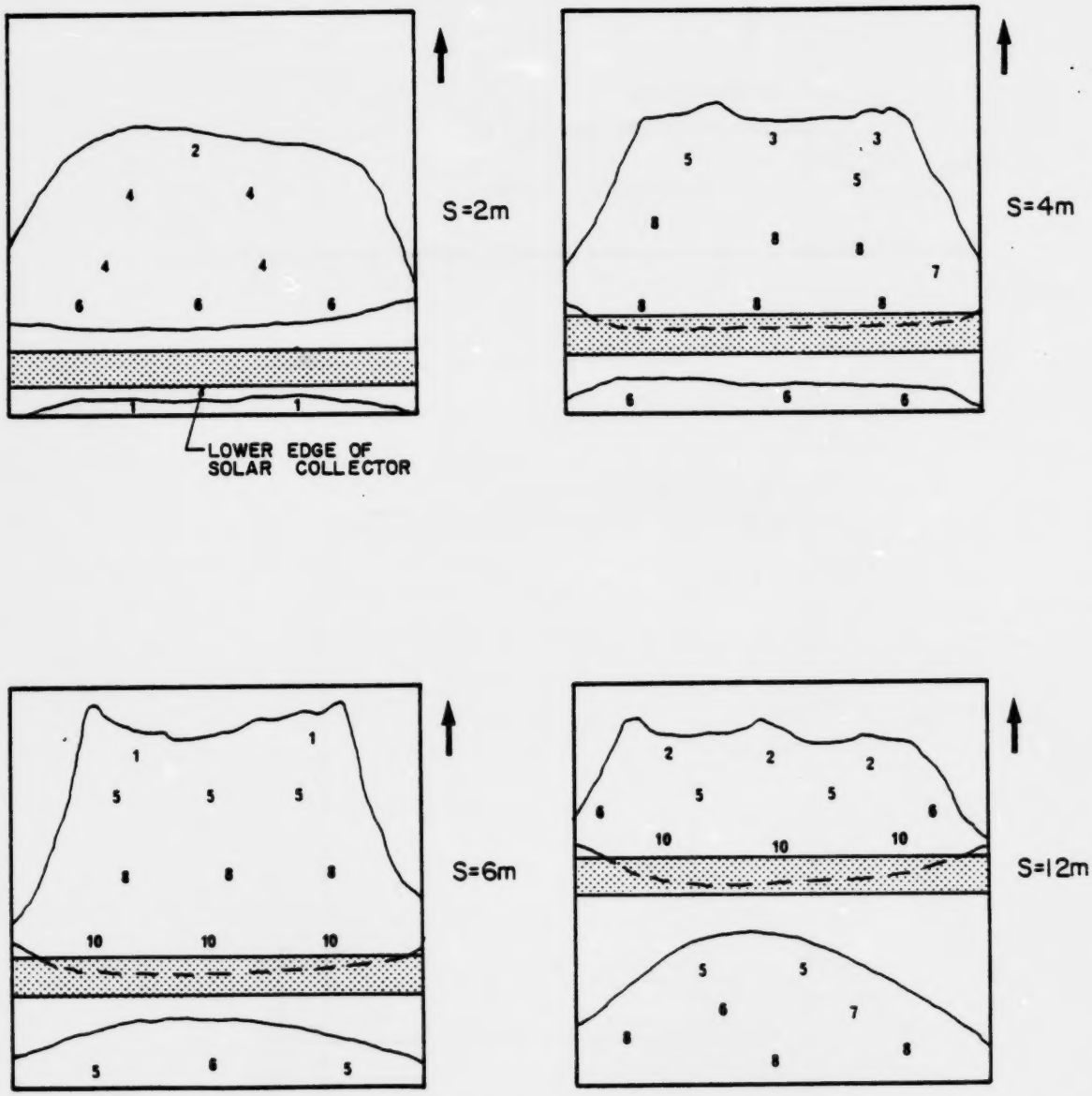


FIGURE 12

SNOW ACCUMULATION ON A HIGH-RISE ROOF

H=30m, g=1m, θ=45°, ϕ=180°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

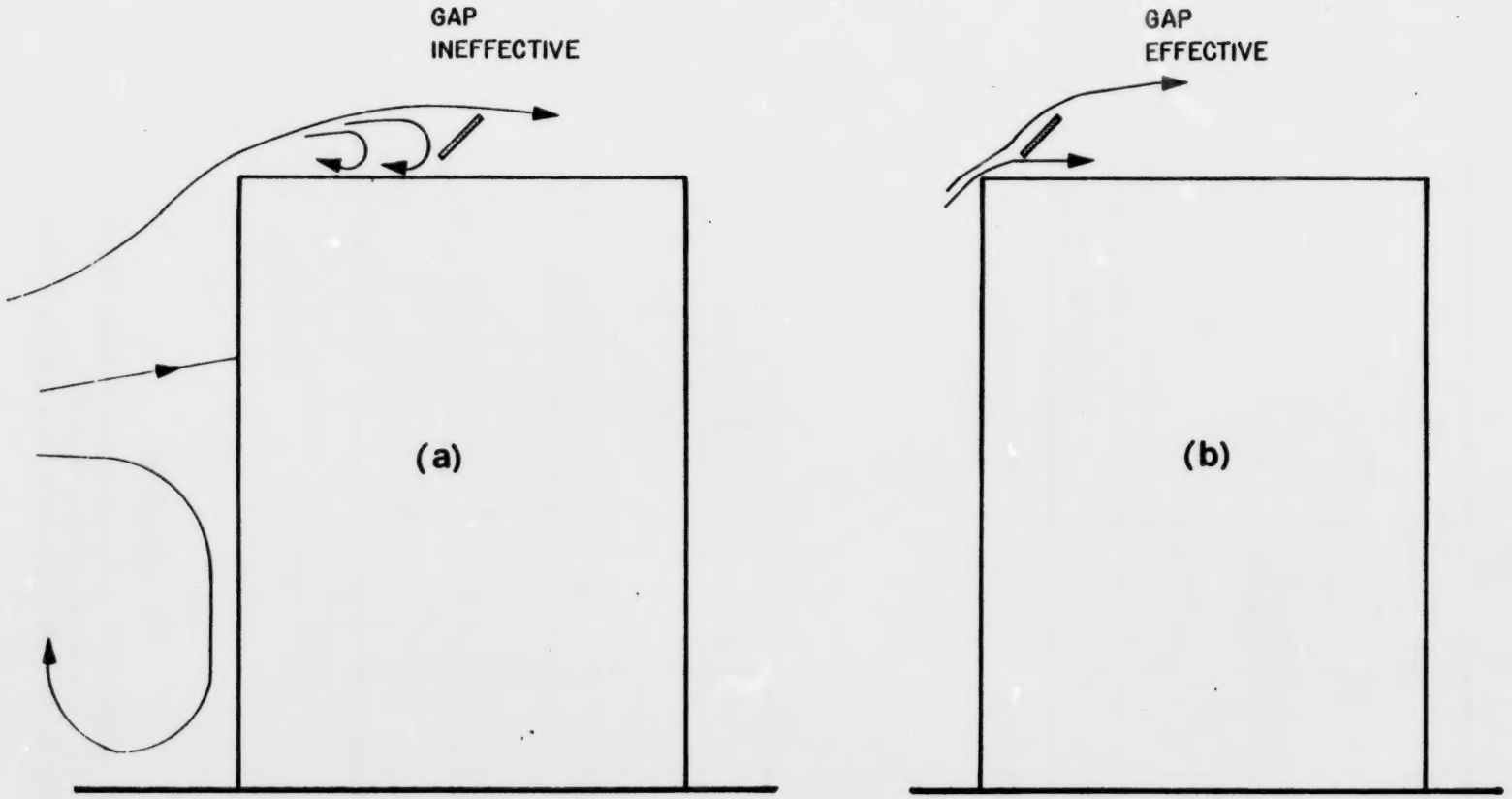


FIGURE 13
WIND FLOW PATTERNS AROUND SOLAR COLLECTOR ON HIGH-RISE ROOF

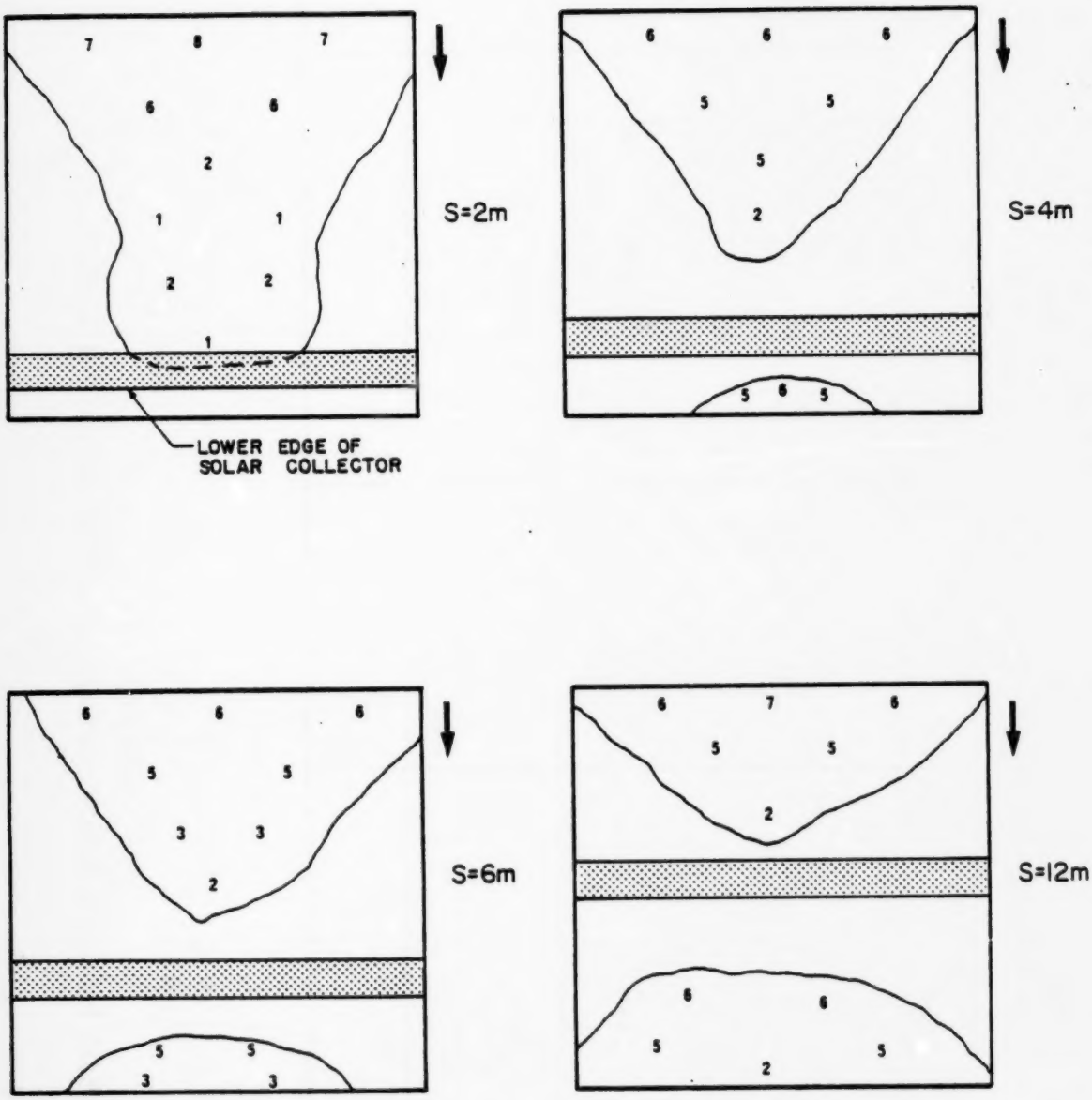


FIGURE 14

SNOW ACCUMULATION ON A HIGH-RISE ROOF

H=30m, g=1m, θ=45°, ϕ=0°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1METRE UNITS

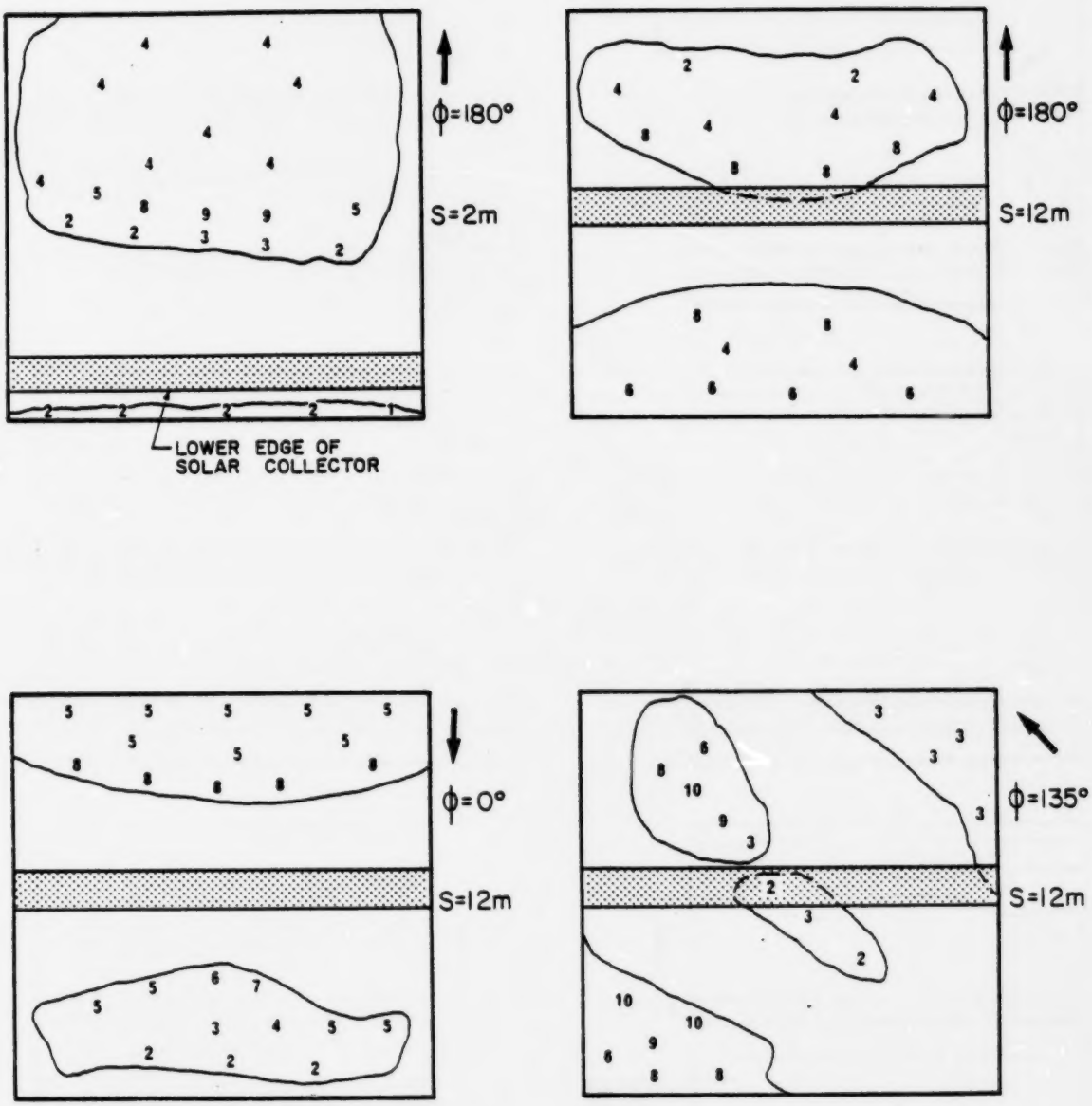


FIGURE 15

SNOW ACCUMULATION ON A HIGH-RISE ROOF

H=30m, g=2m, θ=45°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

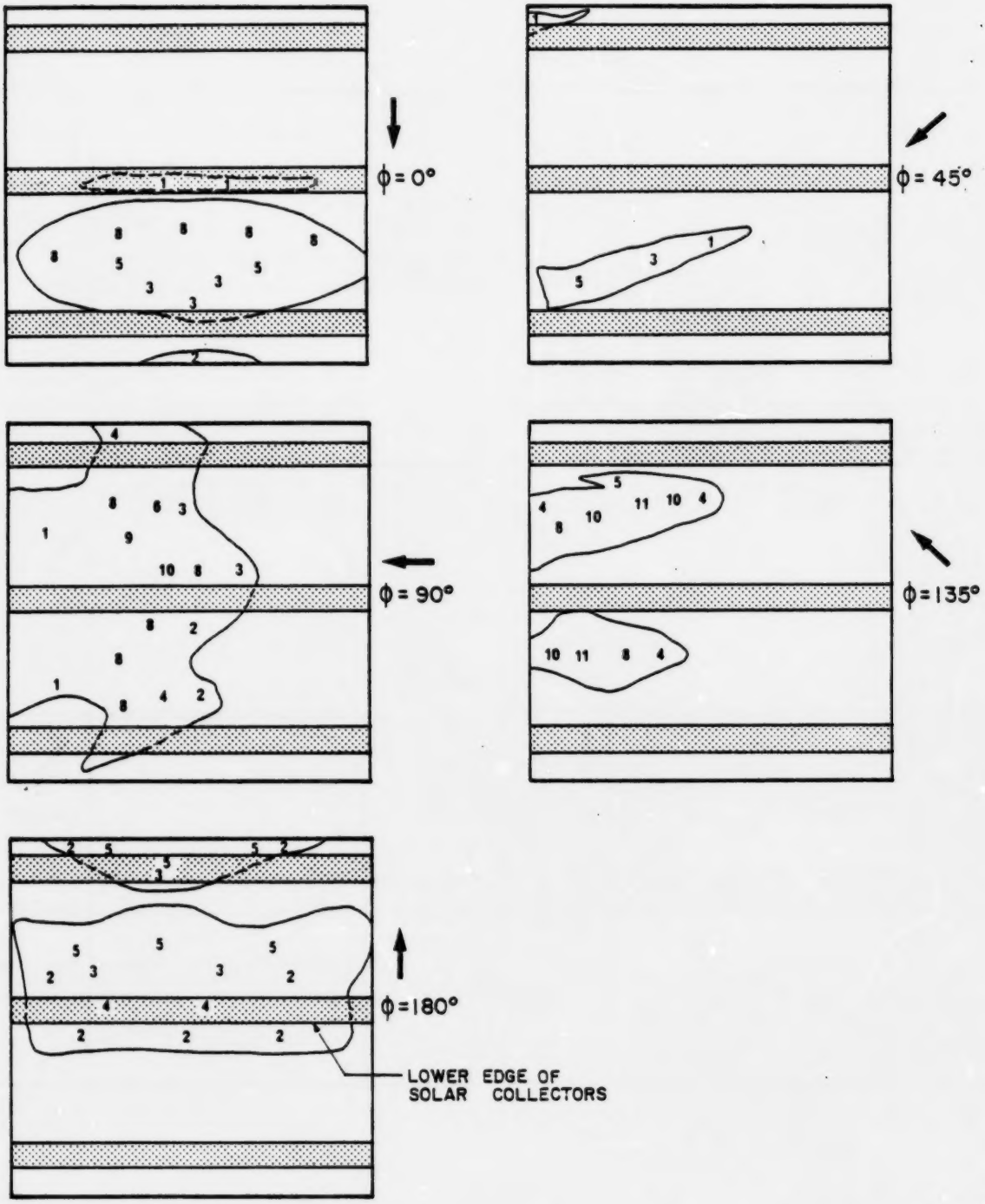


FIGURE 16

EFFECT OF MULTIPLE ROWS, SPACED AT 10m INTERVALS

H=6m, g=1m, θ=45°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

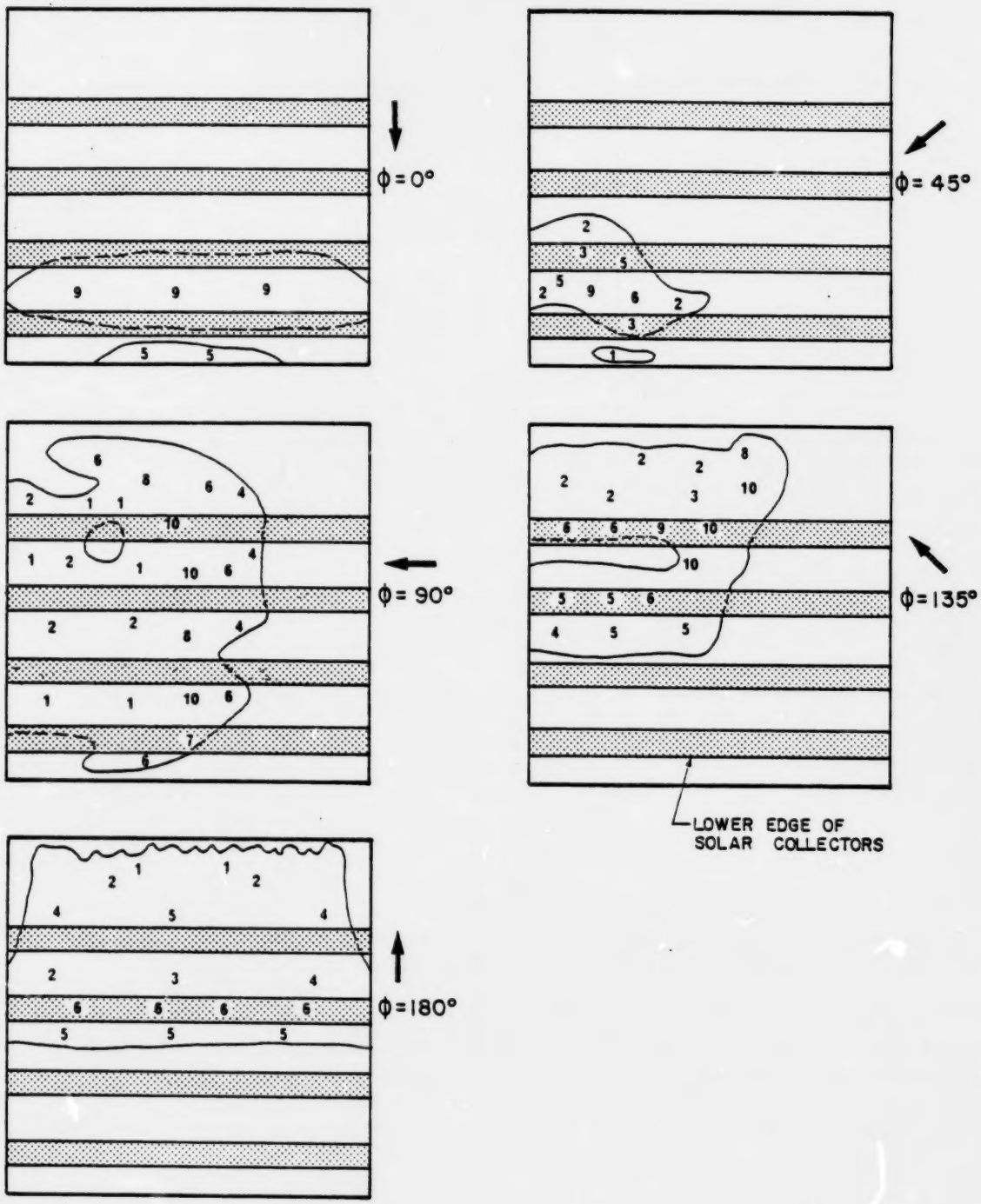


FIGURE 17

EFFECT OF MULTIPLE ROWS, SPACED AT 5m INTERVALS

H=6m, g=1m, θ=45°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

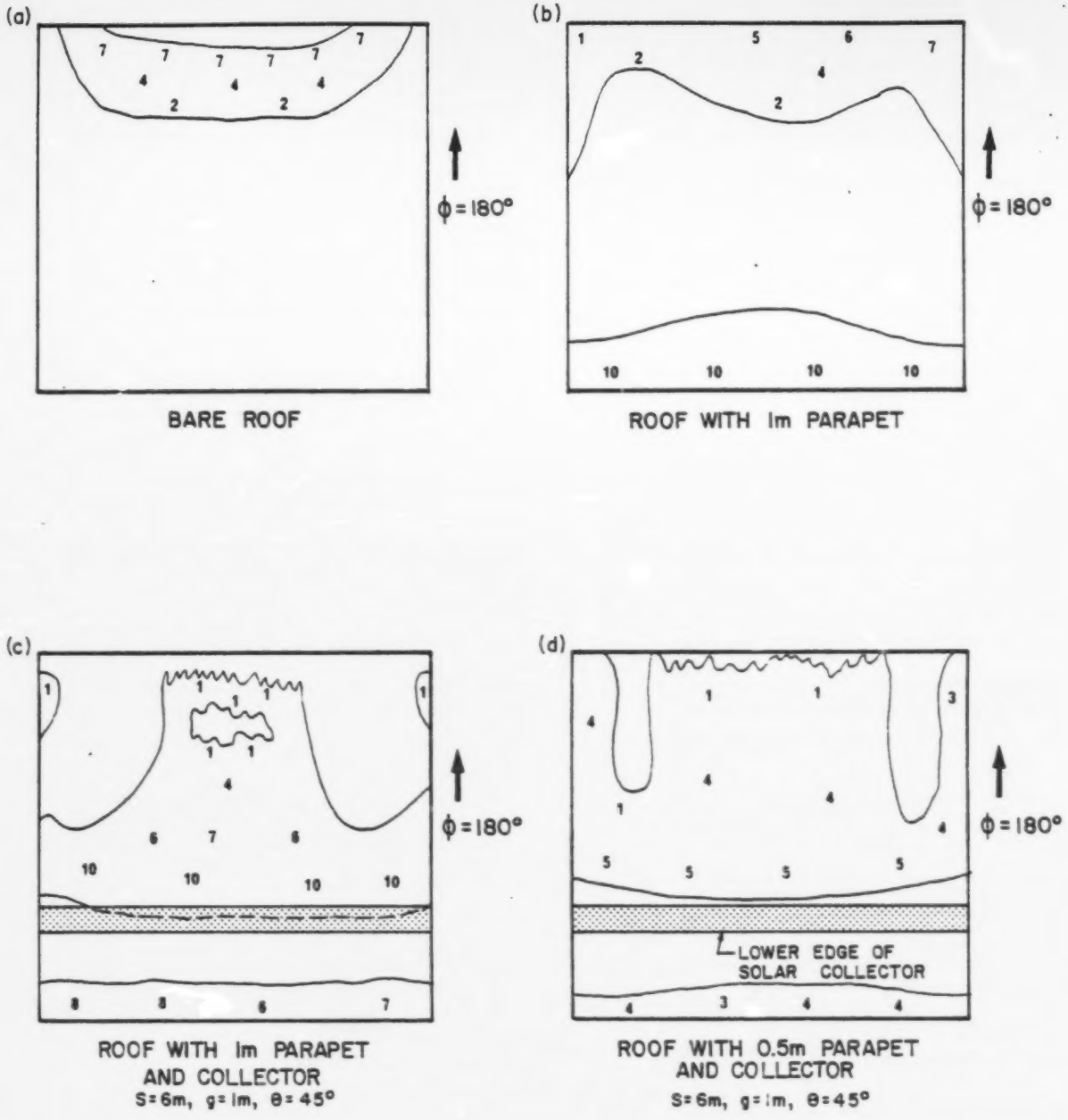


FIGURE 18

EFFECT OF PARAPETS
H=6m

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

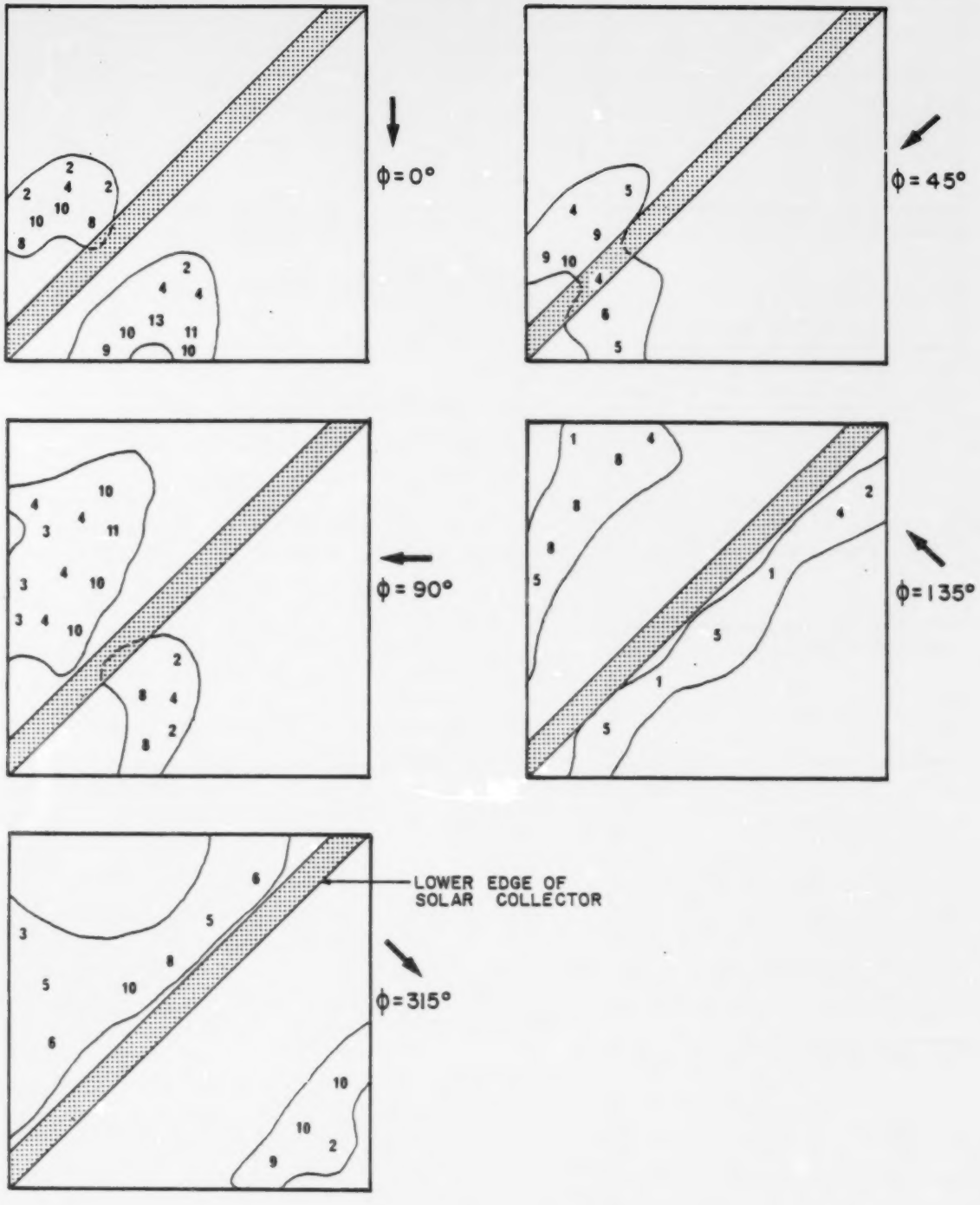


FIGURE 19

EFFECT OF DIAGONAL ORIENTATION OF COLLECTORS

H=6m, g=1m, θ=45°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

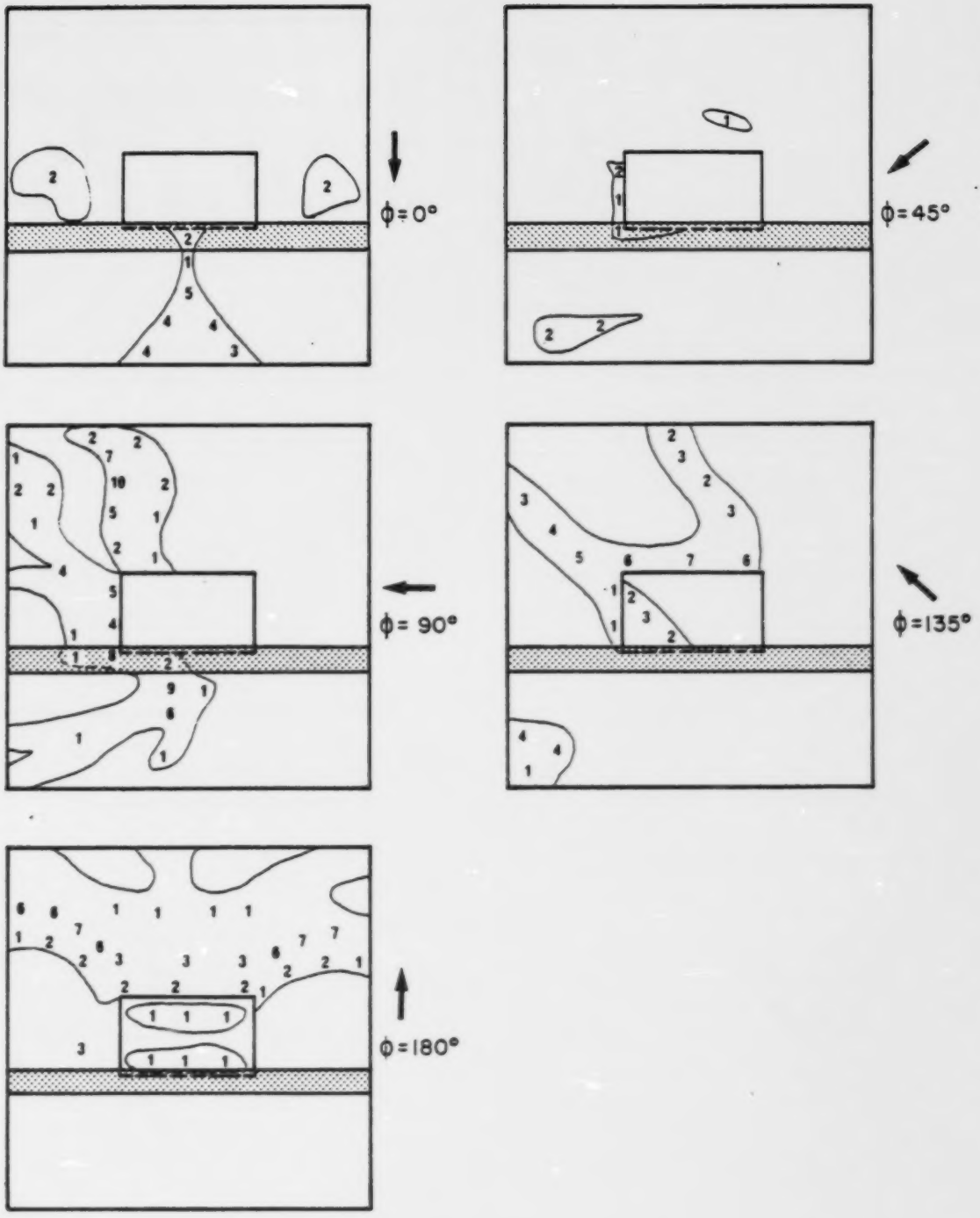


FIGURE 20

EFFECT OF COLLECTOR PROXIMITY TO A 2m HIGH PENTHOUSE

H=6m, g=2m, S=8m, θ=45°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

5	2	0	0	2	5
6	10	4	4	10	5
12	15	18	18	15	10
13	24	18	18	24	12
4	8	8	8	7	4
2	2	0	0	2	2

Mean Roof Snow Depth = 8.0

Maximum Local Snow Depth on Roof = 24.0

GAP = 0.0 m

9	8	5	4	8	10
13	16	8	8	17	14
1	2	10	9	2	1
1	6	4	4	6	1
9	9	4	4	9	9
10	4	2	2	4	10

Mean Roof Snow Depth = 6.4

Maximum Local Snow Depth on Roof = 16.8

GAP = 1.0 m

5	4	2	2	2	2
0	4	2	2	4	0
2	5	5	5	5	2
1	2	5	5	2	1
1	4	2	2	4	1
2	4	4	5	4	2

Mean Roof Snow Depth = 2.4

Maximum Local Snow Depth on Roof = 4.8

GAP = 2.0m

6	7	6	6	7	6
8	7	2	2	7	8
5	2	2	2	2	5
5	2	2	2	2	5
8	7	2	2	7	8
6	7	6	6	7	5

Mean Roof Snow Depth = 4.8

Maximum Local Snow Depth on Roof = 8.0

FIGURE 21

SNOW ACCUMULATIONS SUMMED OVER ALL WIND DIRECTIONS

H=6m, θ=60°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

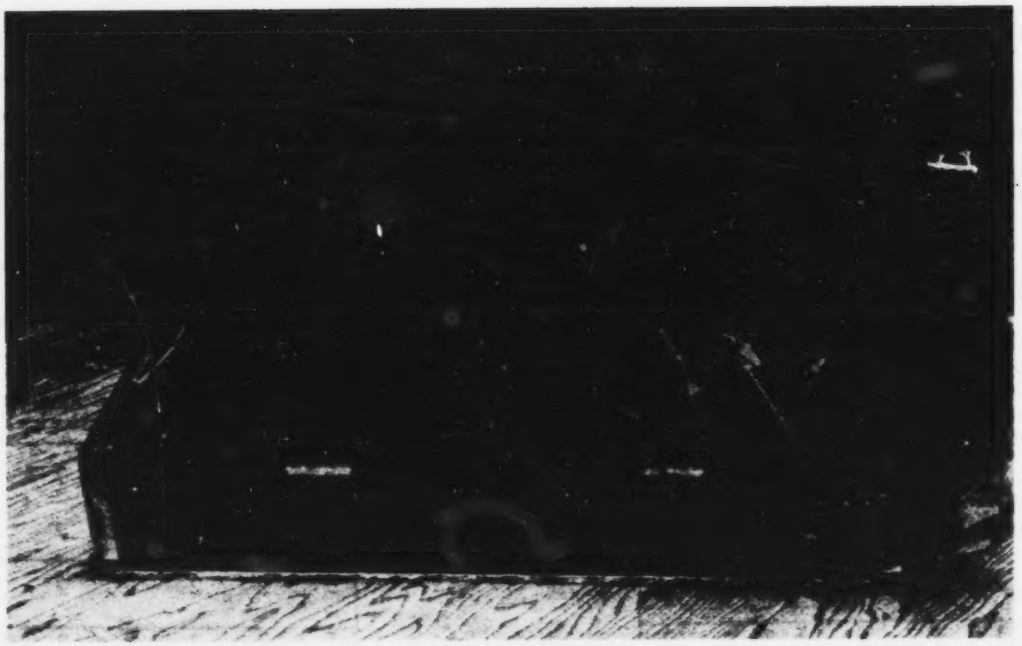


FIGURE 22

WIND TUNNEL MODEL OF 25m x 35m LOW-RISE BUILDING

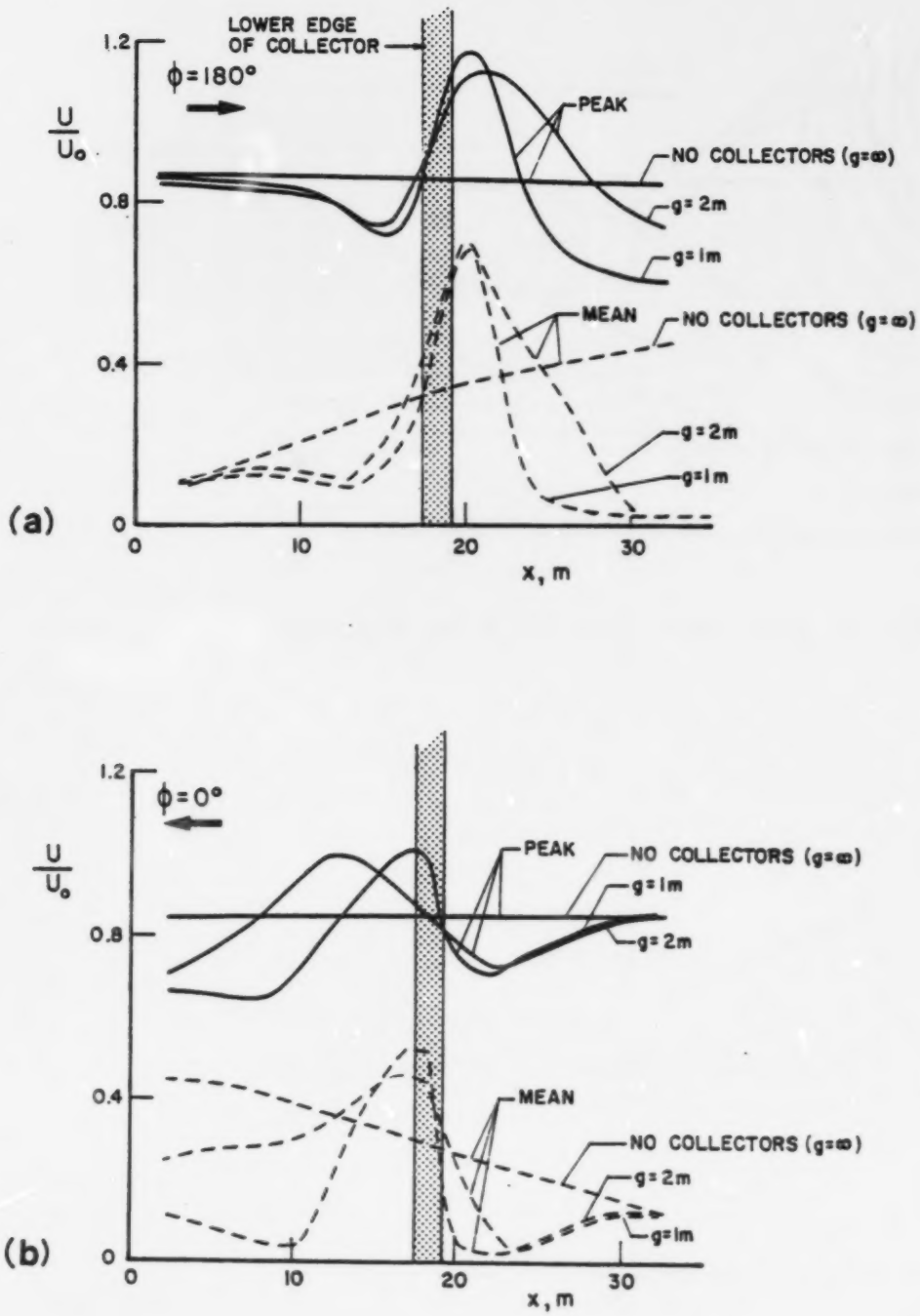
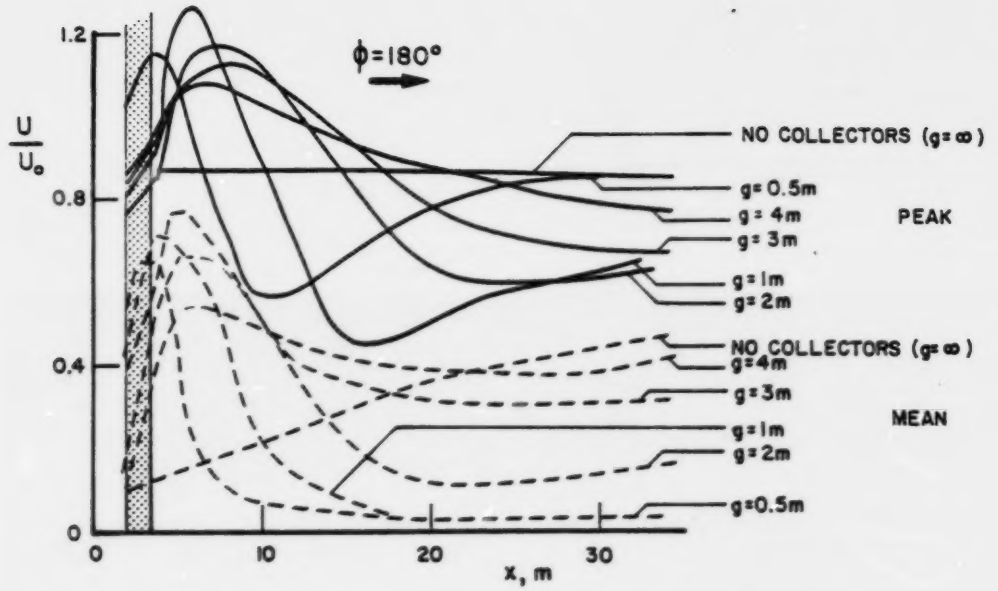
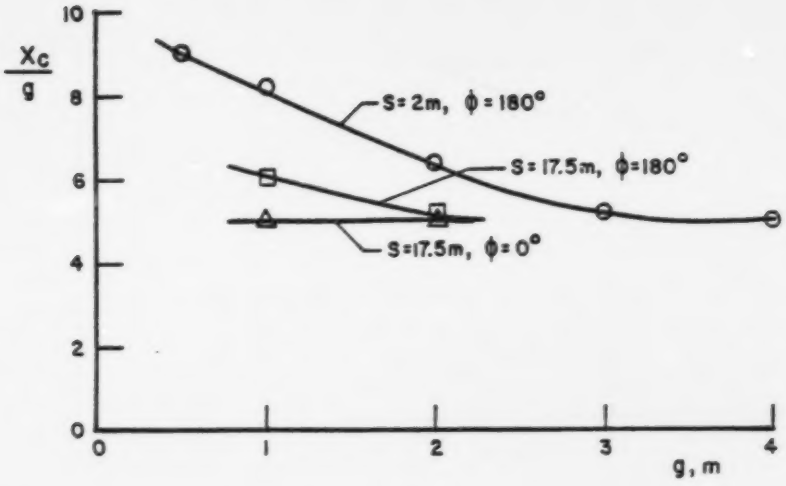


FIGURE 23

WIND SPEED DISTRIBUTION ALONG ROOF CENTRE, 0.2m ABOVE SURFACE
H=6m, S=17.5m, θ=45°



(a) EFFECT OF GAPS FROM 0.5m TO 4.0m FOR S=2m



(b) EFFECT OF GAP ON EXTENT OF ACCELERATED FLOW REGION

FIGURE 24

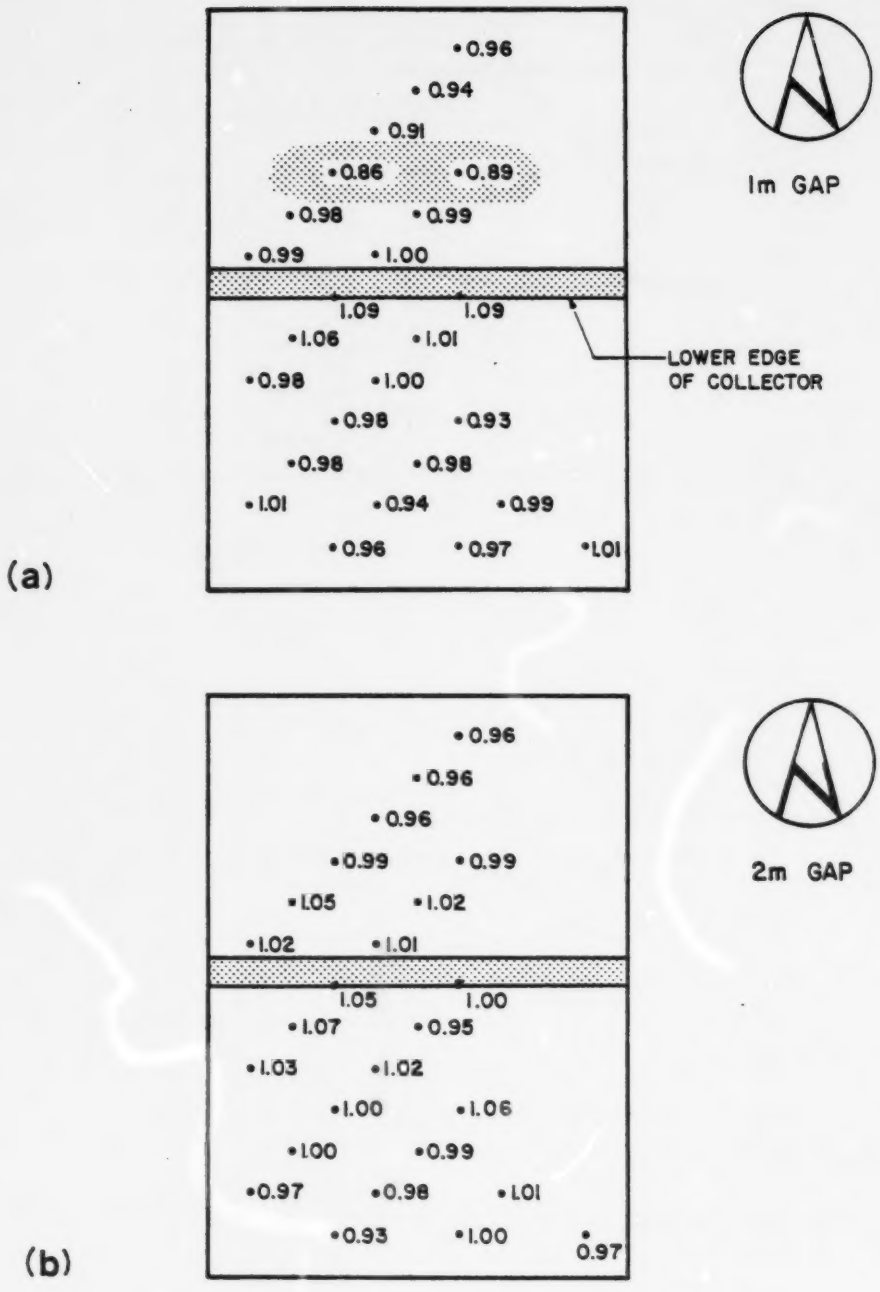
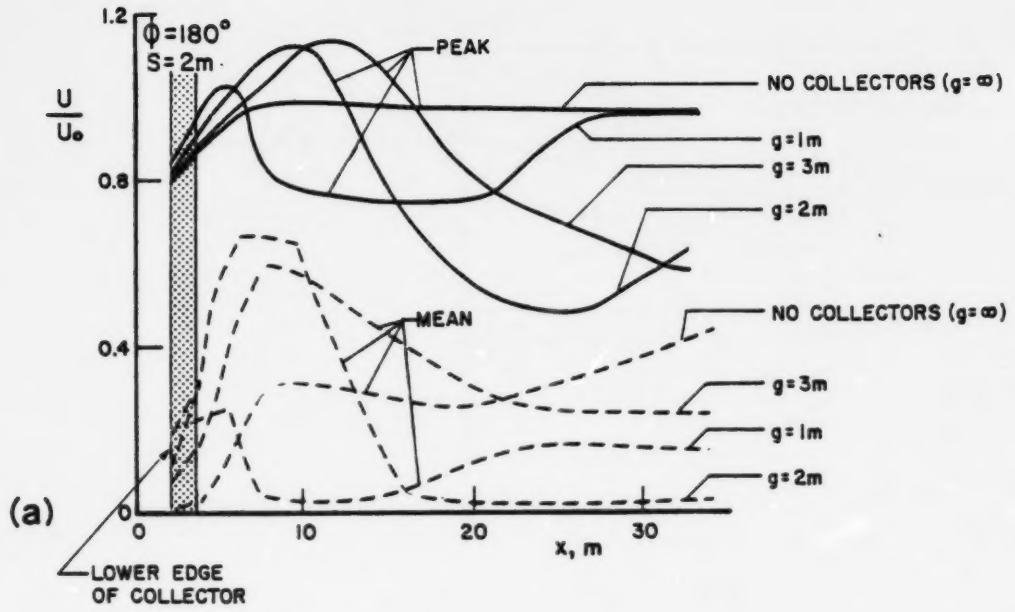


FIGURE 25

RATIO OF ANGLE-AVERAGED PEAK SPEED TO BARE ROOF VALUE

H=6m, S=17.5m, θ=45°



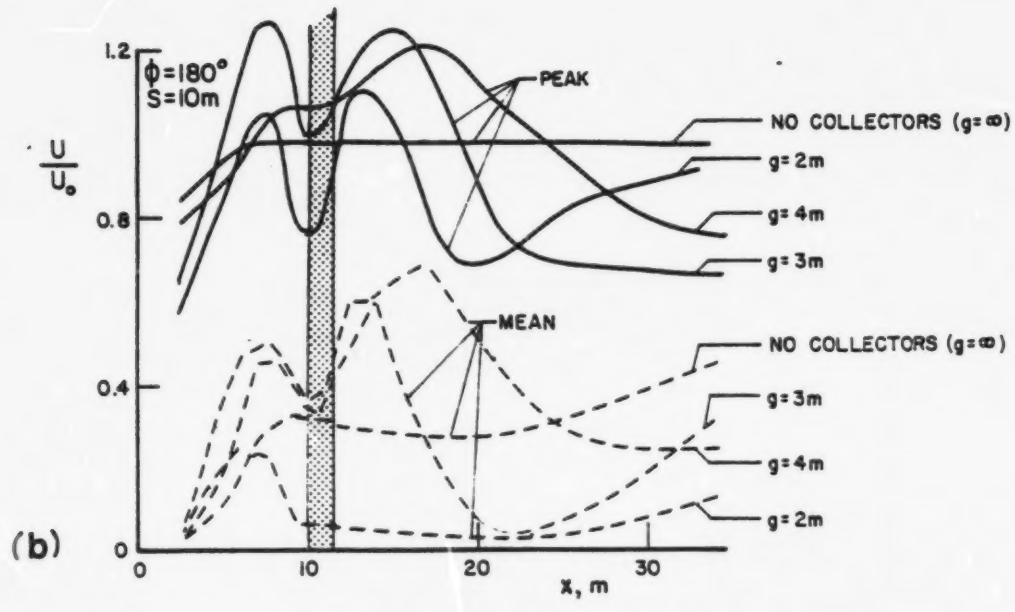


FIGURE 26

WIND SPEED DISTRIBUTION
DUE TO A SINGLE ROW OF COLLECTORS ON A HIGH-RISE ROOF
H=20m, θ=45°

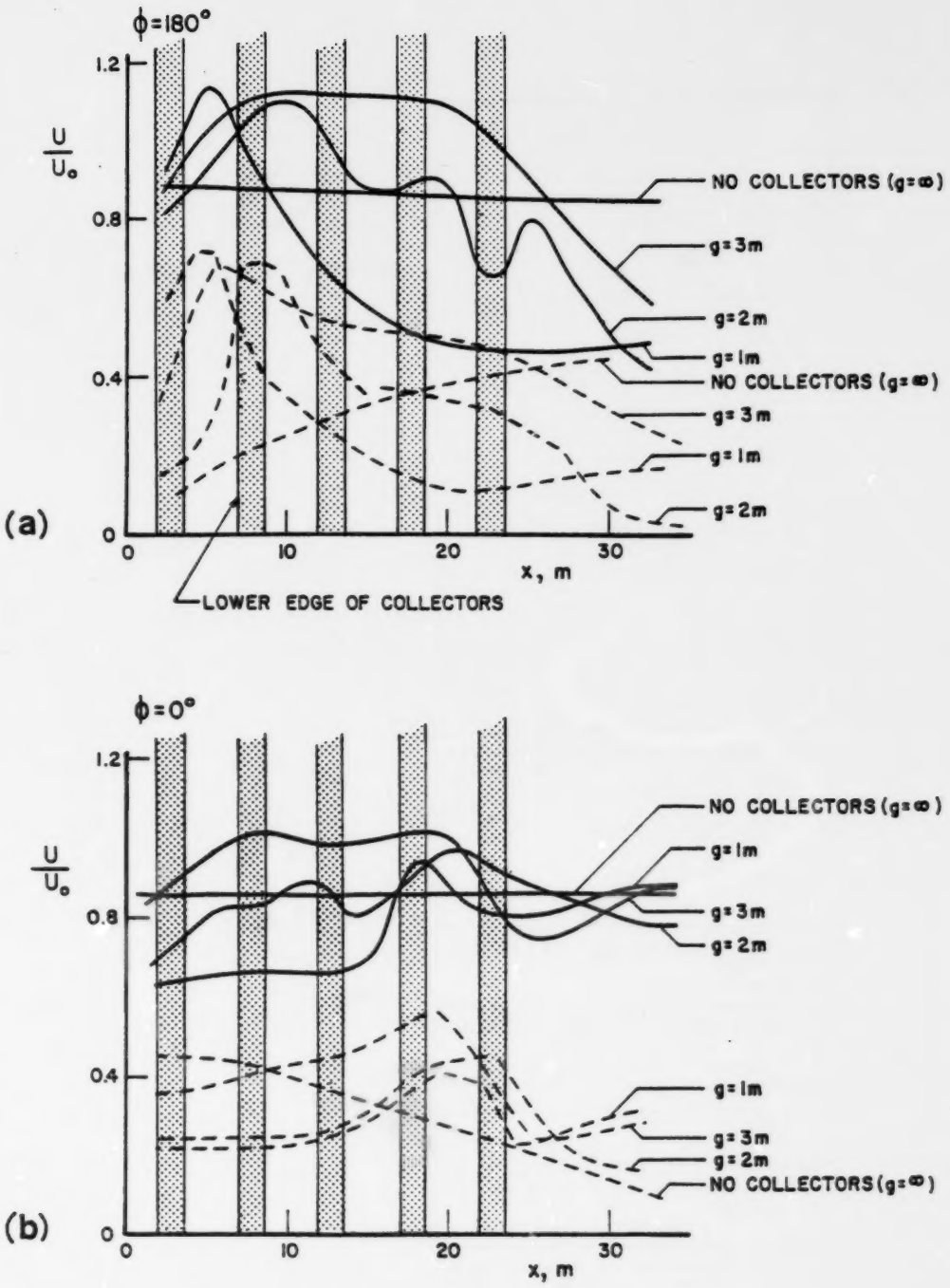
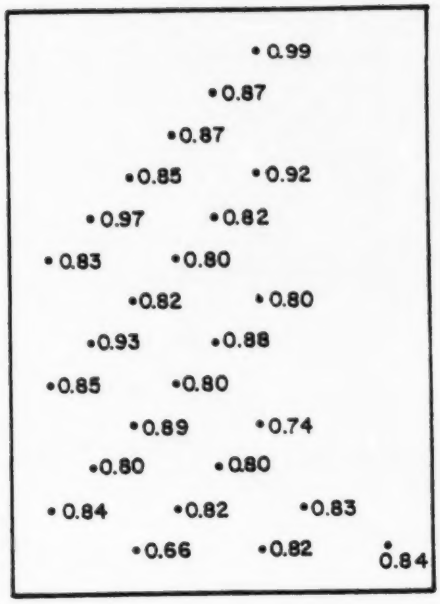


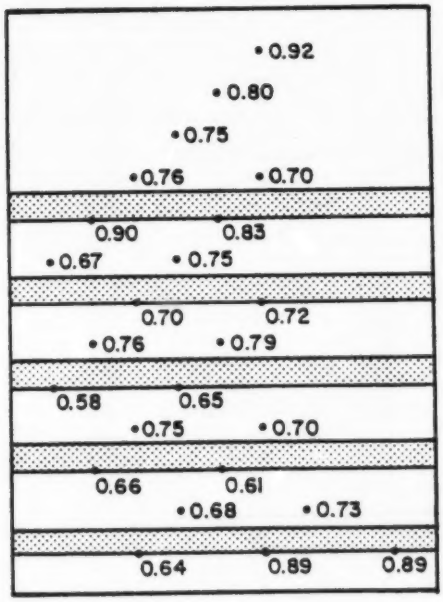
FIGURE 27

WIND SPEED DISTRIBUTION
WITH MULTIPLE ROWS OF COLLECTORS
ROW SPACING=5m, H=6m, θ=45°



(a)

WITHOUT COLLECTORS



(b)

WITH 5 ROWS
OF COLLECTORS

FIGURE 28

EFFECT OF MULTIPLE ROWS OF COLLECTORS
ON PEAK WIND SPEED RATIO FOR $\phi = 90°$
H=6m, g=2m, $\theta = 45°$

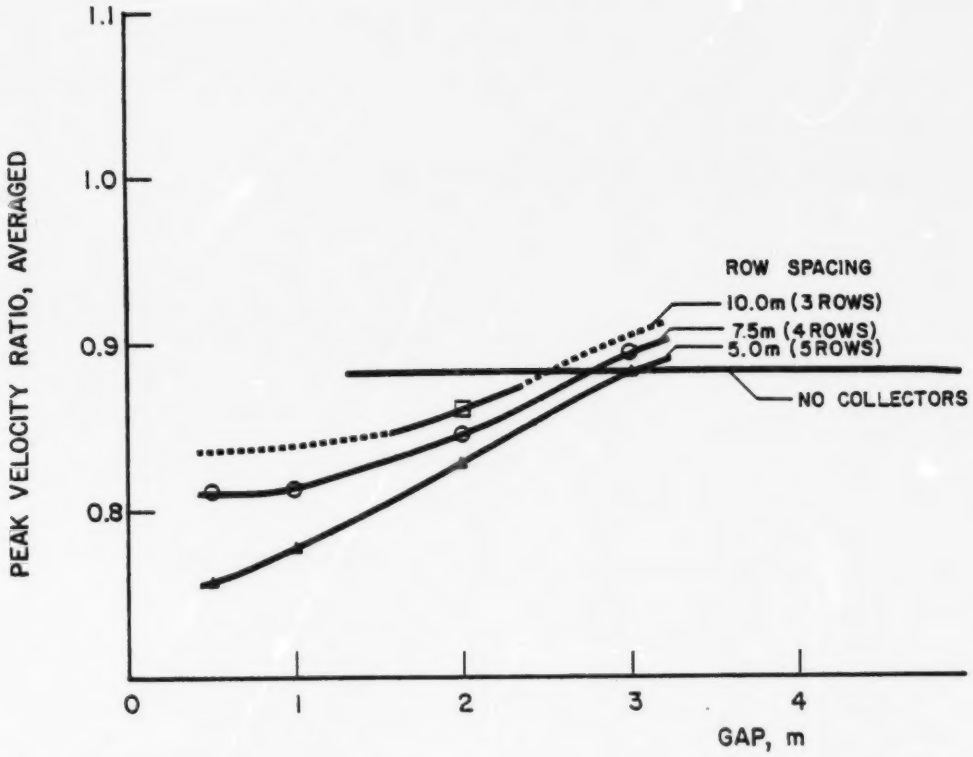


FIGURE 29

EFFECT OF GAP ON THE ANGLE-AVERAGED AND AREA-AVERAGED PEAK VELOCITY RATIO

H=6m, θ=45°

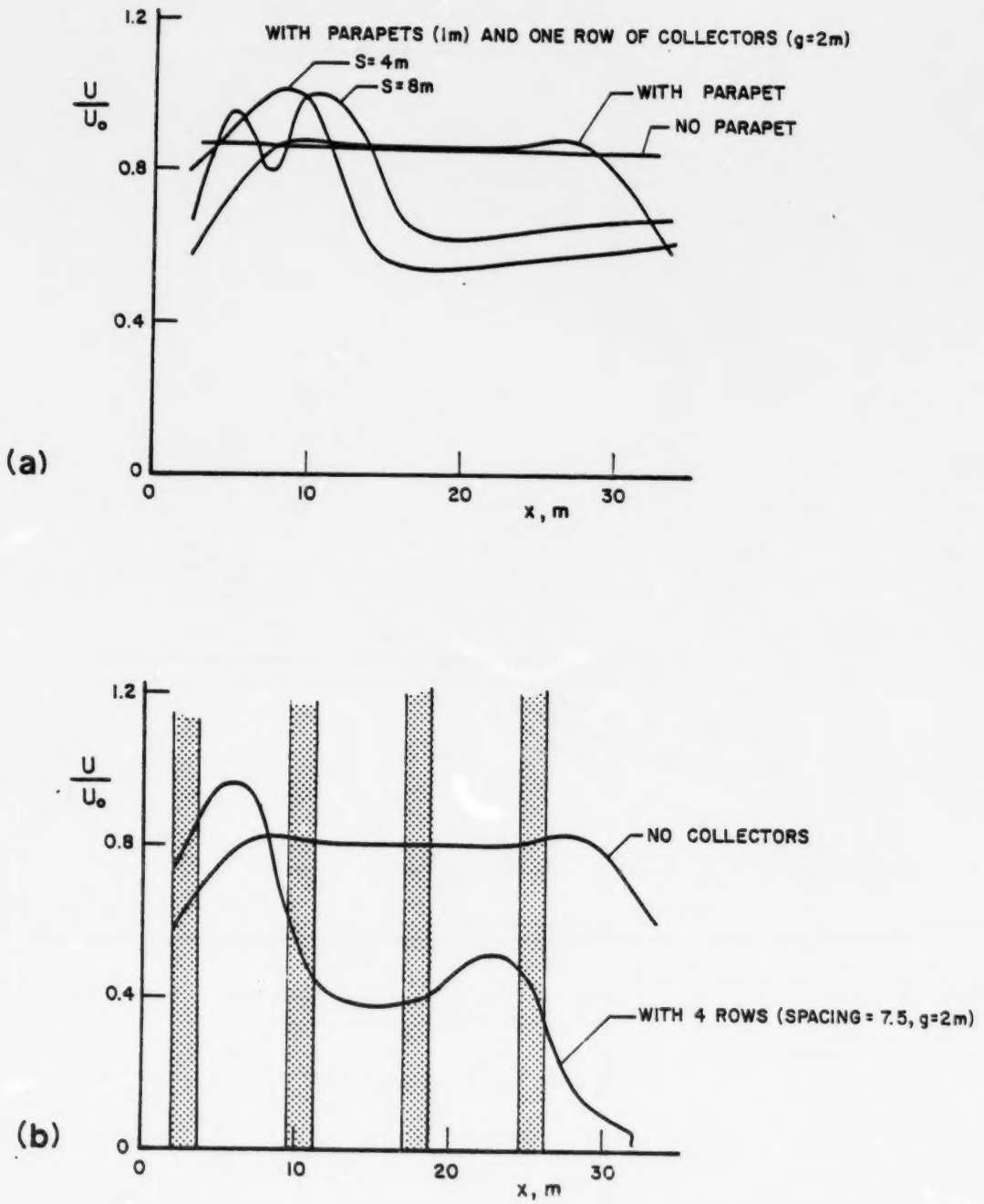


FIGURE 30

EFFECT OF PARAPETS AND SOLAR COLLECTORS ON PEAK WIND SPEED

H=6m, $\theta = 45°$, $\phi = 180°$, PARAPET HEIGHT=1m

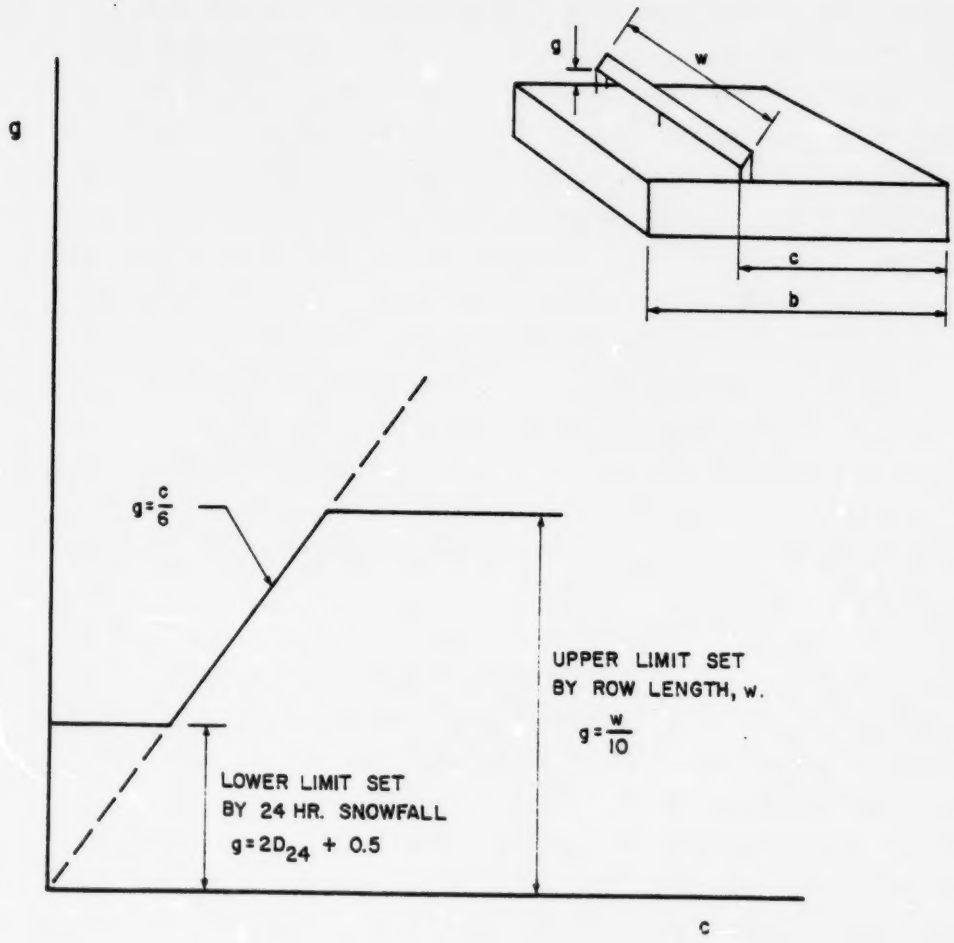


FIGURE 31

GUIDELINES FOR GAP OF A SINGLE COLLECTOR ROW ON A LOW-RISE ROOF

APPENDIX A

SIMULATION OF SNOWDRIFTING

When the wind blows over snow above a certain threshold velocity, the snow particles begin to bounce along in a thin layer above the surface in short hops. This process is named saltation. As the wind speed increases further, the number of airborne particles increases and the layer of saltating particles grows in thickness. However, the thickness of the layer remains small, typically only a few centimeters. At very high wind speeds, when the vertical component of wind turbulence becomes comparable to or greater than the terminal velocity of fall of the snow particles, the particle trajectories become dominated by turbulent diffusion effects rather than saltation and the motion of particles is no longer confined to short hops within a thin layer adjacent to the surface. They may remain airborne for considerable distances. However, at the more common lower wind speeds, saltation tends to dominate. The threshold velocity for the onset of saltation depends greatly on the type of snow that is present.

To exactly simulate every facet of snowdrifting on a physical model is extremely difficult and will probably never be achieved. However, many aspects can be simulated and useful engineering results obtained by the sand - water analogue. A brief theoretical explanation of how this analogue works and which leads to scale factors relating model time and velocity to full scale time and velocity is given in this appendix.

Restricting attention to saltation, two simplifying factors are:

(i) the typical particle path length, ℓ, is very short compared with the typical building sizes;

(ii) the thickness, h_s, of the saltating layer is very small in relation to the typical building height.

The implication of (i) is that significant changes in wind speed around a building will mostly occur over distances large compared with ℓ, i.e. a particle will, except in a few areas of extreme acceleration or deceleration of wind, land in an area where the wind speed is virtually the same as where it took off. The wind speed referred to here is that at a fixed reference height, h_o, slightly larger than h_s. Since h_s, and therefore h_o, is small compared with the building, the detailed shape of the wind speed profile below h_o will be unaffected by the building, taking on a universal form. These considerations lead to the conclusion that for a given type of snow, the volume flux of snow per unit lane width, Q, is completely determined by the local wind speed, U, at height h_o.

$$Q = f(U) \qquad (1)$$

Q is defined conveniently so as to facilitate conversion to snow depths, as the volume the airborne snow would occupy when at rest on the ground, including all air spaces between particles. The path length, ℓ, does not enter into Equation 1 and will not do so as long as it is small compared with the distances over which significant accelerations or decelerations of wind occur. In non-dimensional form, Equation 1 may be written

$$\bar{Q} = \frac{Q}{h_o U_T} = Cf\ (\bar{U}) \qquad (2)$$

where $\bar{U} = U/U_T$, U_T is the threshold wind speed for the onset of saltation and C is a dimensionless constant.

In the absence of snowfall, the rate of increase of snow depth, D, in two-dimensional conditions is given by

$$\frac{dD}{dt} = \frac{-dQ}{dx} \qquad (3)$$

where x = coordinate in direction of wind.

Equation 2 may be used to eliminate Q from Equation 3, resulting in

$$\frac{dD}{dt} = -Ch_o U_T \frac{df(\bar{U})}{dx} = -Ch_o U_T f' \frac{d\bar{U}}{dx} \qquad (4)$$

where $f' = \frac{df(\bar{U})}{d\bar{U}}$

In non-dimensional form Equation 4 may be written

$$\frac{d\bar{D}}{d\bar{t}} = -f' \frac{d\bar{U}}{d\bar{x}} \qquad (5)$$

where $\bar{D} = D/b$, $\bar{x} = x/b$, $\bar{t} = \frac{CU_T t h_o}{b^2}$, and b is a reference dimension of the building concerned.

Equation 5 describes drifting in two-dimensional wind flow. In three-dimensional flow additional terms arise on the right hand side but they would not change the essentials of the present discussion. The sand - water analogue simulates snowdrifting because it is essentially governed by a relation similar to Equation 5. It satisfies the criteria that ℓ and h_o are small compared with model buildings, and the function f in the transport rate relation, Equation 2, is of the same form as for snow transport.

Figure 1 shows the non-dimensional relation between snow volume transport and wind speed for typical conditions. For snow we may arbitrarily set C = 1 in Equation 2 and, taking h_o = 1m, U_T is typically 3m/s. Measurements of volume flux of silica sand in water indicated C = 43 and U_T = 0.10 m/s, where h_o is taken to be 5mm. Figure 1

includes data points for silica sand in water with these values of C and U_T and it can be seen that they lie close to the curve for snowdrifting. Thus, when geometrically scaled models in the sand - water analogue produce patterns of U that mirror closely those at full scale, the non-dimensional snow depths D tend also to mirrors those at full scale.

To relate model time and speed to full scale time and speed, the fact that t and U are the same for both may be used. Denoting model values by m and full scale values by p (for prototype) it follows that

$$t_m = t_p \frac{C_p h_{op} U_{Tp}}{C_m h_{om} U_{Tm}} \left(\frac{b_m}{b_p}\right)^2 \quad \text{and} \quad U_m = U_p \left(\frac{U_{Tm}}{U_{Tp}}\right) \qquad (6)$$

Using the values of C, h_o and U_T given earlier for model and full scale it is deduced that for a 1:200 scale model $t_m = t_p/290$ and $U_m = U_p/30$. It is interesting to note that t_m is proportional to the model scale, $b_m:b_p$, squared. Thus, a doubling of the model size requires running the sand - water analogue for four times longer to produce the same non-dimensional snow depths. The physical reasons for this are that not only are the speed gradients reduced in proportion to 1/b on larger models, implying reduced deposition rate, but the depth of sand must also reach a physically greater value to give the same non-dimensional depth.

Figures 2 and 3 show results of model tests on flat roofs at scales 1:100, 1:200 and 1:400. The tests were all run at the same speed and started with the same non-dimensional sand depth, D, evenly deposited over the roof area. The times for each run were 20 minutes, 5 minutes and 1.25 minutes respectively, which are all equivalent to 24 hours at full scale according to the model law, Equation 6, and should therefore produce the same snow

accumulations. It can be seen that the snow depth patterns are very similar, verifying the theoretical dependence of model time on model scale.

The discussions of this appendix have aimed to explain theoretically the sand - water technique which was originally developed on an empirical basis by Theakston. Use of the simplification that the particle path length is short makes it unnecessary to enter into the complexities of what determines the particle trajectory. Therefore, parameters such as particle Reynolds number, Froude number, terminal velocity and density ratio which determine the trajectory, did not enter into the discussion. However, there will be circumstances where such parameters do play a significant role and where caution and judgment are required in interpreting the model results. This particularly applies when looking at the fine scale details of the snow accumulations which may be influenced by particle path length.

In the present application the dimensions of the solar collectors and the gap between the collectors and roof were generally larger than the particle path length but not by the same margin as for the building as a whole. Thus, the assumption of small path length represented more of an approximation for solar collectors. Nonetheless, it was considered the results would still serve as a useful guide to snow accumulations particularly when used in combination with wind tunnel measurements of wind speed distributions.

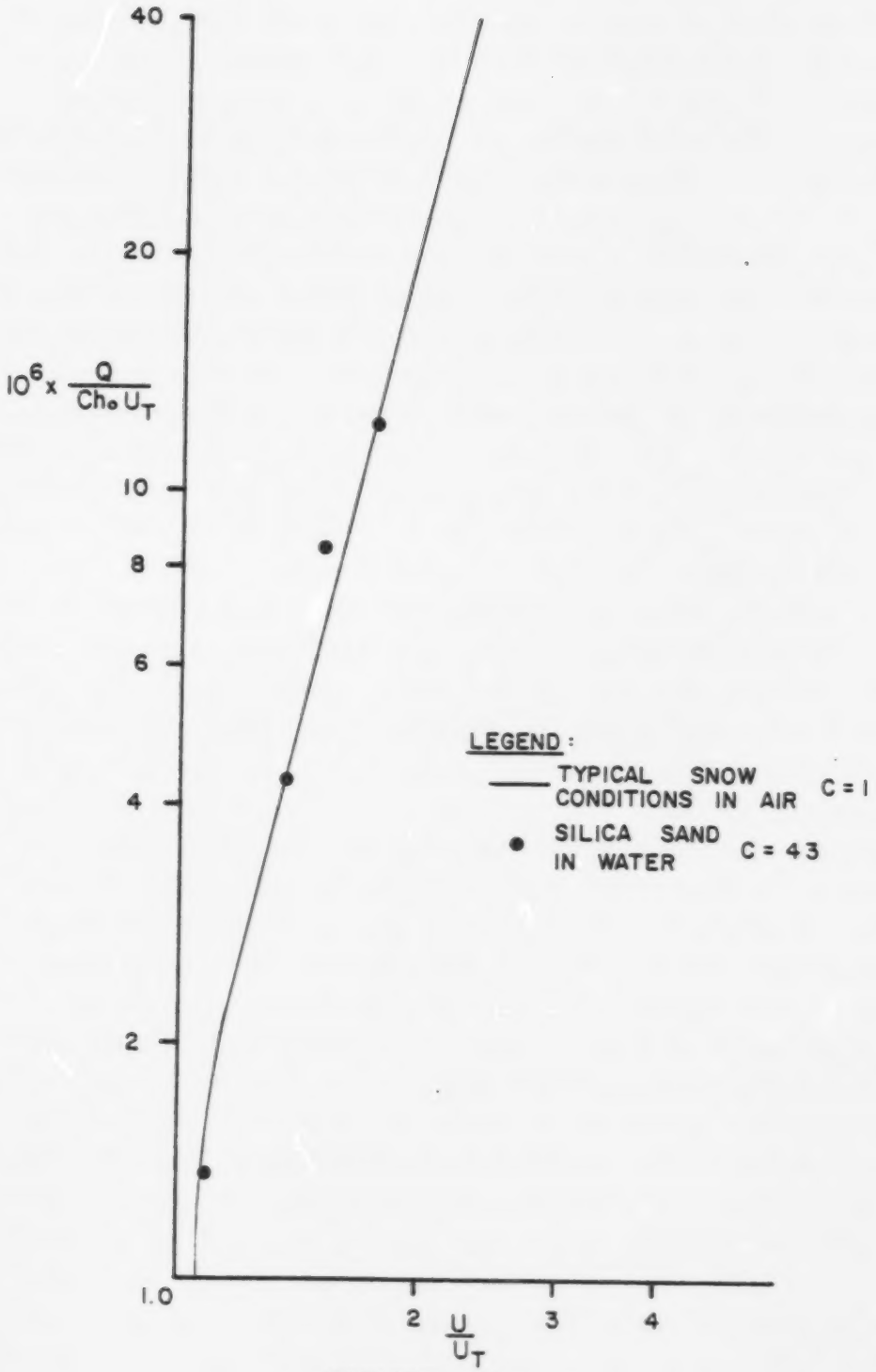


FIGURE AI
VOLUME TRANSPORT OF SNOW IN AIR AND SILICA SAND IN WATER

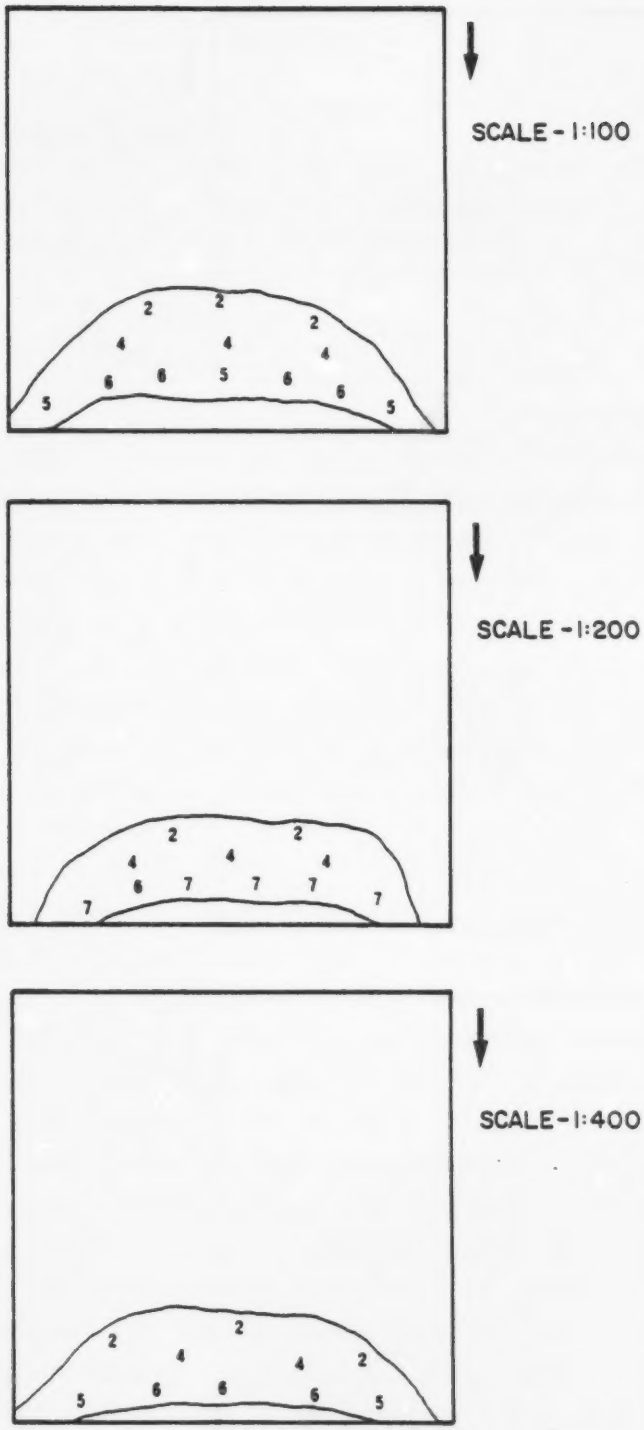


FIGURE A2

SNOW ACCUMULATION ON A LOW-RISE ROOF

H=6m, $\phi = 0°$

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

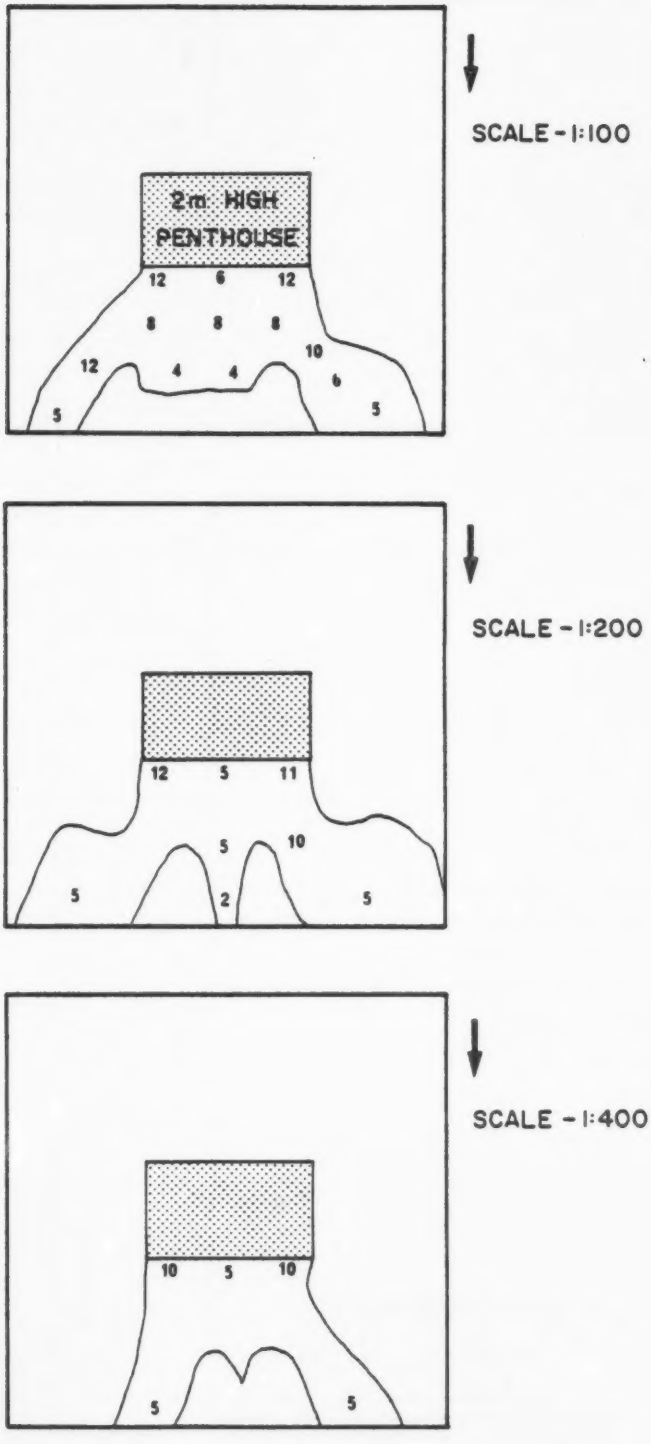


FIGURE A3

SNOW ACCUMULATION ON A LOW-RISE ROOF

H=6m, ϕ= 0°

NUMBERS INDICATE SNOW ACCUMULATION DEPTHS IN 0.1 METRE UNITS

APPENDIX B

WIND SIMULATION

Full scale data show that the mean wind speed, U, increases with height, Z, approximately according to the relation

$$\frac{U}{U_{REF}} = \left(\frac{Z}{Z_{REF}}\right)^{\alpha}$$

where U_{REF} is the value of U at a reference height, Z_{REF}. The exponent α depends on the roughness of the terrain. Most buildings are in suburban areas for which $\alpha = 0.25$ is appropriate. Figure 1 shows the mean velocity profile in the water flume generated by the spire-roughness technique as described in Reference B1. It agrees well with Equation 1 with $\alpha = 0.25$. The measurements of water velocity were made using a propellor type current meter. A similar velocity profile was generated in the wind tunnel.

The spires and roughness created a boundary layer about 0.3m thick, approximately 1/1200th of the full scale planetary boundary layer thickness in the water flume. The length scale of the boundary layer turbulence was also approximately 1/1200th of full scale. Ideally it would have been 1/200th of full scale, the same as for the models, but such large turbulence scales cannot be achieved in the water flume. The difference between turbulence and model scales is considered unlikely to affect the main conclusions of the present tests. One reservation exists, however, concerning the model results on high-rise buildings. Because of the difference in boundary layer and model scales the turbulence intensity at the high-rise roof level would have been low compared with full scale and this probably increased the size of the separated flow region at the roof. This is discussed in Section 5.4. In the

wind tunnel the boundary layer was at a scale of 1:500 compared with the model scale of 1:50.

Reference

B1 Irwin, P.A. - "Design and Use of Spires for Natural Wind Simulation", National Research Council, N.A.E. Report LTR-LA-233, August, 1979.

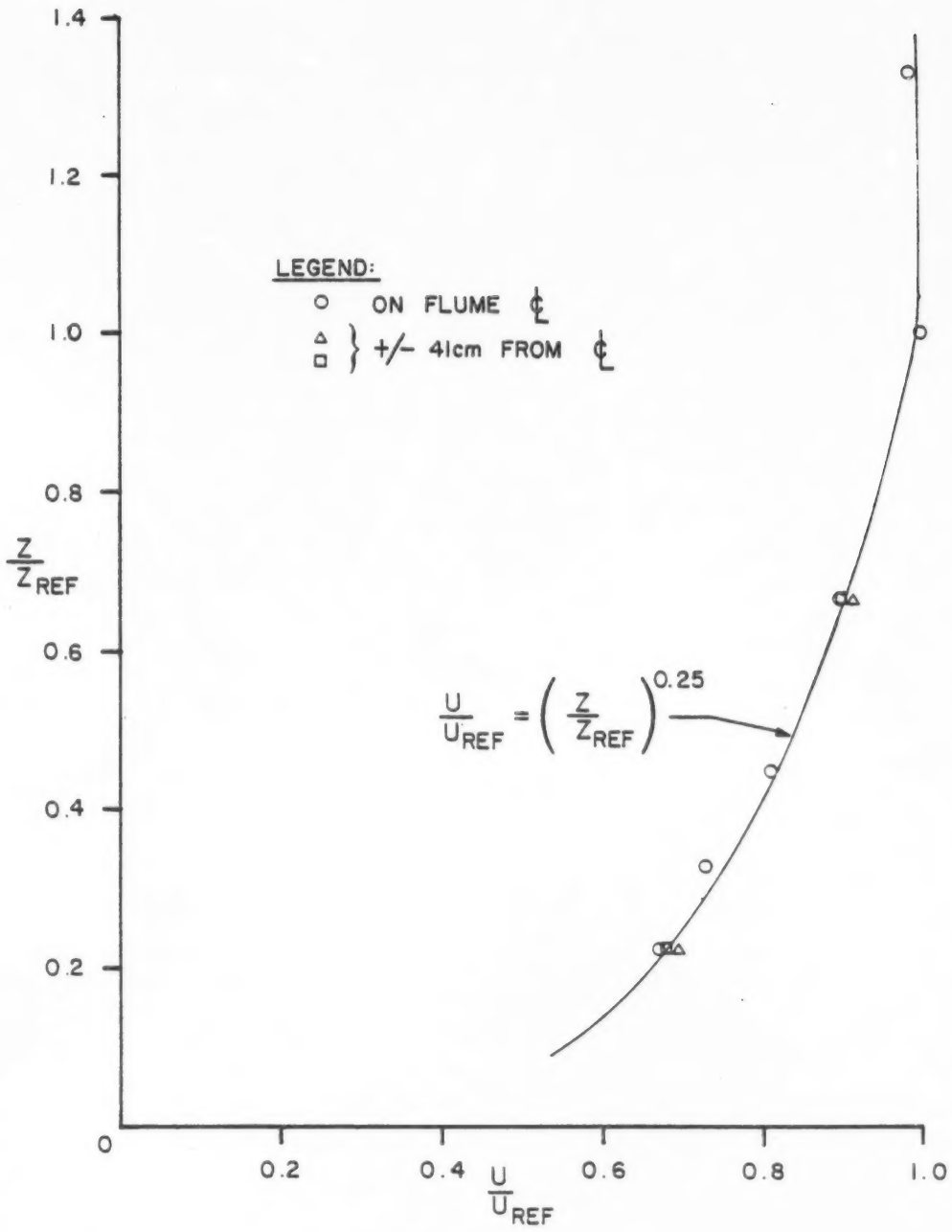


FIGURE BI

VELOCITY PROFILE IN SIMULATED WIND